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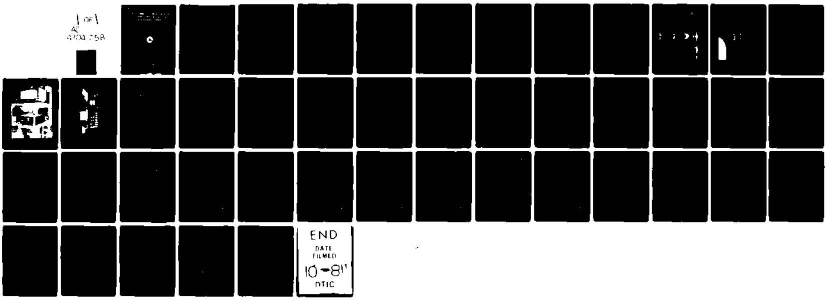

Report No. FAA-CT-81-34

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THE USE OF GROUNDSPEED IN A WIND SHEAR AND THE FLIGHT EVALUATION OF A RADAR-ALTIMETER-BASED SYSTEM FOR THE MEASUREMENT OF GROUNDSPEED

AD A104758

David Lawrence

FINAL REPORT

JULY 1981

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16. Abstract

The use of groundspeed in combination with airspeed has been considered and shown to be an effective aid in the execution of an approach and landing in a heavy jet transport airplane. A flight dynamics analysis shows that the response of such aircraft to sudden changes in headwind is quite sluggish, requiring more than 100 seconds for equilibrium conditions to be regained in the worst case.

A feasibility demonstration model of a radar-altimeter-based system for the measurement of groundspeed has been subjected to a limited in-flight evaluation. It is a self-contained unit requiring no ground-based equipment and no on-board equipment other than the small flush transmit and receive antennas and the associated cable runs.

While the current unit does not meet the desired accuracy standard ($\Delta = \pm$ 3 knots, or less), it approaches it at times, and greater accuracy can be achieved with further development. Responsiveness to rapidly changing groundspeed matched that of the reference inertial navigation system; and satisfactory groundspeed tracking was maintained during turning, climbing, and descending flight.

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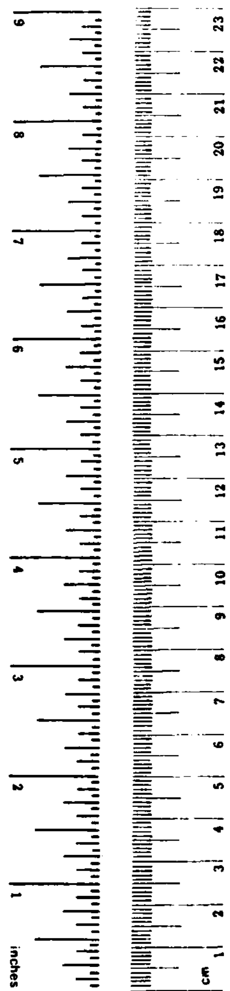
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

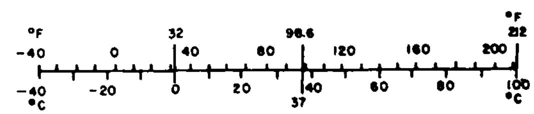
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

The purpose of the work described in this report was to evaluate the performance of a feasibility demonstration model of an airborne radar-based system for the measurement of airplane groundspeed at low altitudes (50 to 1,000 feet) and speed ranges between 100 and 250 knots.

BACKGROUND.

Extensive moving base flight simulation studies (references 1 and 2) sponsored by the Wind Shear Program Office (ARD-310) of the Federal Aviation Administration (FAA) have shown that airplane groundspeed in combination with indicated airspeed, frequently updated and presented to pilots in a prominent and easily interpreted display, materially contributes to their ability to fly through a sharply varying headwind profile such as is experienced in a wind shear.

Wind shear is a generic term for a variety of wind conditions characterized by rapid spatial variation of wind speed and/or direction. Depending on whether turbulence is present or not, rapid temporal variation of the wind may also occur, but the end result remains the same; that is, an airplane flying through the affected airmass is subjected to rapid and potentially dangerous changes in indicated airspeed. The inertia of the airplane prevents a rapid response to a sudden change in airspeed. In large jet transport airplanes, the problem is aggravated by the relatively long response time of the engines. While this situation has improved greatly in recent years, a large turbofan engine nonetheless requires 4 to 5 seconds to accelerate from a flight idle condition to full output.

A groundspeed display, to be of value, must be located where it can be monitored continuously against indicated airspeed. The difference between the two quantities is a fair approximation to the headwind, and the rate at which that difference changes is a measure of the shear. The groundspeed is of value in another way. If the threshold headwind and the distance to touchdown are known, it is possible to determine critical lower boundary values of groundspeed and indicated airspeed, which if observed will permit a safe flightpath to be flown through to touchdown. At the very least, a timely indication will be provided that the approach is hazardous and should be terminated.

Considerable interest centers on the development of an accurate, responsive, and inexpensive device for measuring groundspeed. The most accurate system currently available, an inertial platform, is very expensive because it is designed to provide far more data than the required groundspeed and does so with an accuracy which exceeds the present requirements. A far cheaper device is needed but one that shares with the inertial platform the advantage of being self-contained. The subject of this test and evaluation meets these requirements, or certainly has the potential for doing so. It is a feasibility demonstration model of a system based on the correlation of radar altimeter ground return signals. It requires no ground-based equipment of any kind or any sensors or transducers other than the transmitting and receiving antennas. It also functions as a radar altimeter; so, it is essentially two instruments in one.

ANALYTICAL CONSIDERATIONS.

Airplane groundspeed is the vector sum of true airspeed and windspeed. At low pressure altitudes ($h \leq 2,000$ feet), the difference between true airspeed and indicated airspeed is 3 percent or less, and an acceptable approximation for head wind is

Head wind $\cong$ indicated airspeed - groundspeed.

The error starts to be too large above 2,000 feet, and a better head wind approximation is

Head wind $\cong$ true airspeed - groundspeed.

The measurement of true airspeed requires that total pressure, total temperature, and static pressure all be accurately known. Either of the two preceding equations is preferable to the full solution of the wind triangle, which requires in addition to true airspeed, the track angle, groundspeed, and heading in order to implement it. Crosswind information is lost by taking the simpler approach. However, landing accident analysis shows that errors in the control of airspeed, altitude, and altitude rate are far commoner causal factors than errors in track or lateral position, so the lost information is not usually of the greatest importance.

A wind shear of 10 knots in 100 feet vertically is severe, but can occur. An airplane in a 3.5° approach at an initial airspeed of 140 knots would lose very nearly 1.5 knots of airspeed per second, flying into a headwind diminishing at the stated rate of shear, unless the groundspeed increased correspondingly. If to this requirement is added the further requirement that the airplane negotiate a 6-feet-per-second downdraft, the remaining acceleration margin will be diminished by a further 1/2 knot per second. For many jet transport airplanes at a high gross weight, very nearly the full acceleration capability would be required, and any increase in the shear or downdraft would cause an increase in the descent rate that could not be arrested.

The equation governing longitudinal acceleration is

$$\dot{V} = g\left(\frac{T-D}{W} - \sin\gamma\right)$$

where: D = Airplane drag, pound (lb),
g = Acceleration due to gravity, feet per second squared (ft/s^2)
T = Thrust, lb
$\dot{V}$ = Longitudinal acceleration, ft/s^2
W = Airplane gross weight, lb
γ = Flight path elevation angle

Some typical figures applicable to a common commercial jet transport are:

T_{max} = 50,000 lb
D = 32,500 lb
W = 150,000 lb

Inserting these figures and setting γ = -3° yields an acceleration of 3.2 knots per second.

It is evident then that a jet transport airplane making a landing approach through a severe wind shear does not have a very large performance margin. If the wind shear is aggravated by a downdraft as can happen in the latter stages of a thunderstorm, aircraft performance may be taxed to the limit to avoid premature contact with the ground. It is clearly necessary, therefore, when flying through a headwind shear to monitor the important flightpath variables throughout an approach, particularly the final 1,000 feet.

An analysis (reference 3) that sheds some further light on jet transport behavior in a wind shear encounter is presented in expanded form in appendix A. The airplane response to a change in headwind closely approximates a first order system. The airplane at the start of its landing approach is stabilized on the glide slope with landing gear and flaps down, and for the duration of the calculation, thrust and attitude are held constant. The time constant for the ensuing response to a step change in the head wind is about 22 seconds. A stable airplane subjected to such a disturbance seeks to regain its original trimmed airspeed, which it does in four time constants (89 seconds) with an altitude loss (in addition to the scheduled loss) of 200 feet (for a $\Delta V = -25$ feet per second). This example is hypothetical to be sure, but it serves to demonstrate the sluggishness of a heavy jet transport and to stress the importance of closely monitoring the critical flightpath variables during an approach.

TEST ARTICLE

System and equipment descriptions have been provided by the manufacturer. Much of this material is proprietary, and for the purposes of this report, descriptive material will be limited to a very general description of the major components.

The equipment is a low cost version of the General Electric CORAN™ (Correlation of Radar Altimetry for Navigation) groundspeed sensor. It measures groundspeed (heading velocity component only in this instance) using a ground return correlation technique. The implementation is entirely airborne, and no ground equipment of any kind is necessary. The version tested operates between 50 and 1,000 feet at speeds between 100 and 250 knots.

DISCUSSION

SYSTEM DESCRIPTION.

The equipment as installed in the FAA Technical Center Grumman Gulfstream 1 test airplane consists of five major components:

TRANSMITTER. The transmitter consists of a 1.075-gigahertz (GHz) crystal oscillator, a switch for pulse generation, a frequency multiplier (X4), and the transmitting antenna (figure 1). The transmitter runs at a fixed pulse width and power level and has the following characteristics:

Frequency = 4.3 GHz
Pulse Width = 37 nanoseconds
Duty Cycle = 0.1% maximum
Peak Power = 105 watts

ANTENNAS. There is a single transmitting antenna and a receiving antenna pair. The transmitting antenna is mounted centrally (butt line 0) on the fuselage undersurface between the wing trailing edge and the horizontal stabilizer. The receiving antennas are mounted slightly to the left of center (offset was a matter of convenience only) about 10 feet ahead of the transmit antenna to achieve the necessary line-of-sight isolation from the latter. There is a 6-1/2-inch longitudinal separation between the front and rear members of the pair. All three antennas are extremely small and produce an extremely small increment of aerodynamic drag (figures 1 and 2).

RECEIVER. A switching network in the receiver alternately selects the front and rear elements of the antenna pair. The outputs are processed and fed to the sampling circuits in which a 3-channel sampling and analog-to-digital conversion scheme is used. The receiver subassembly has the following characteristics:

Type = Superheterodyne
Noise figure = 8.0 decibel (dB)
Bandwidth = 28 megahertz (MHz)
Automatic gain control (AGC) dynamic range = 60 dB

DIGITAL PROCESSOR. The digital processor performs the system controlling function and the correlation function by which airplane groundspeed is sensed. The transmitter pulse repetition

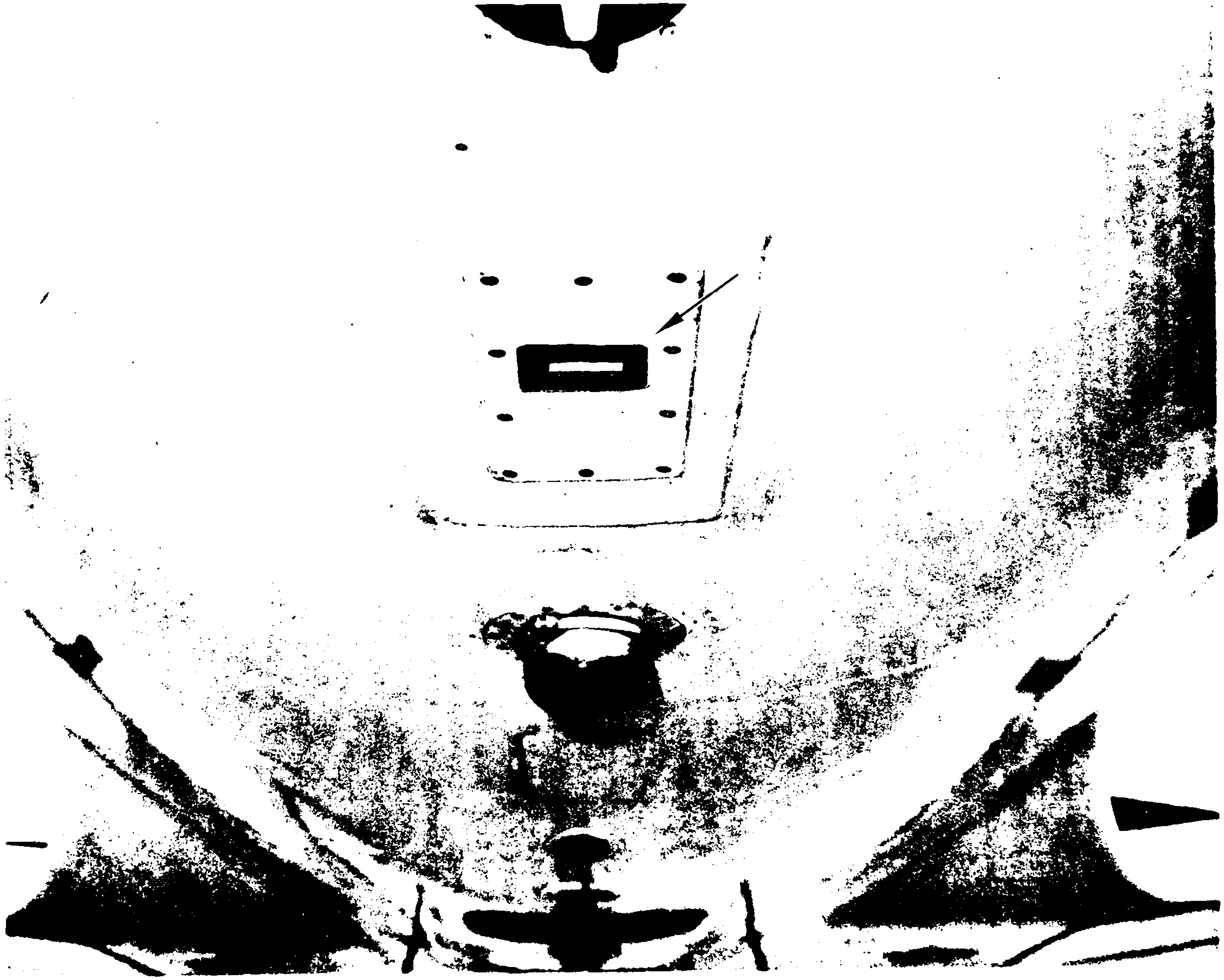

FIGURE 1. CORAN™ TRANSMITTING ANTENNA LOCATED AT FS 517 ON FUSELAGE UNDERSURFACE OF GULFSTREAM 1 AIRPLANE

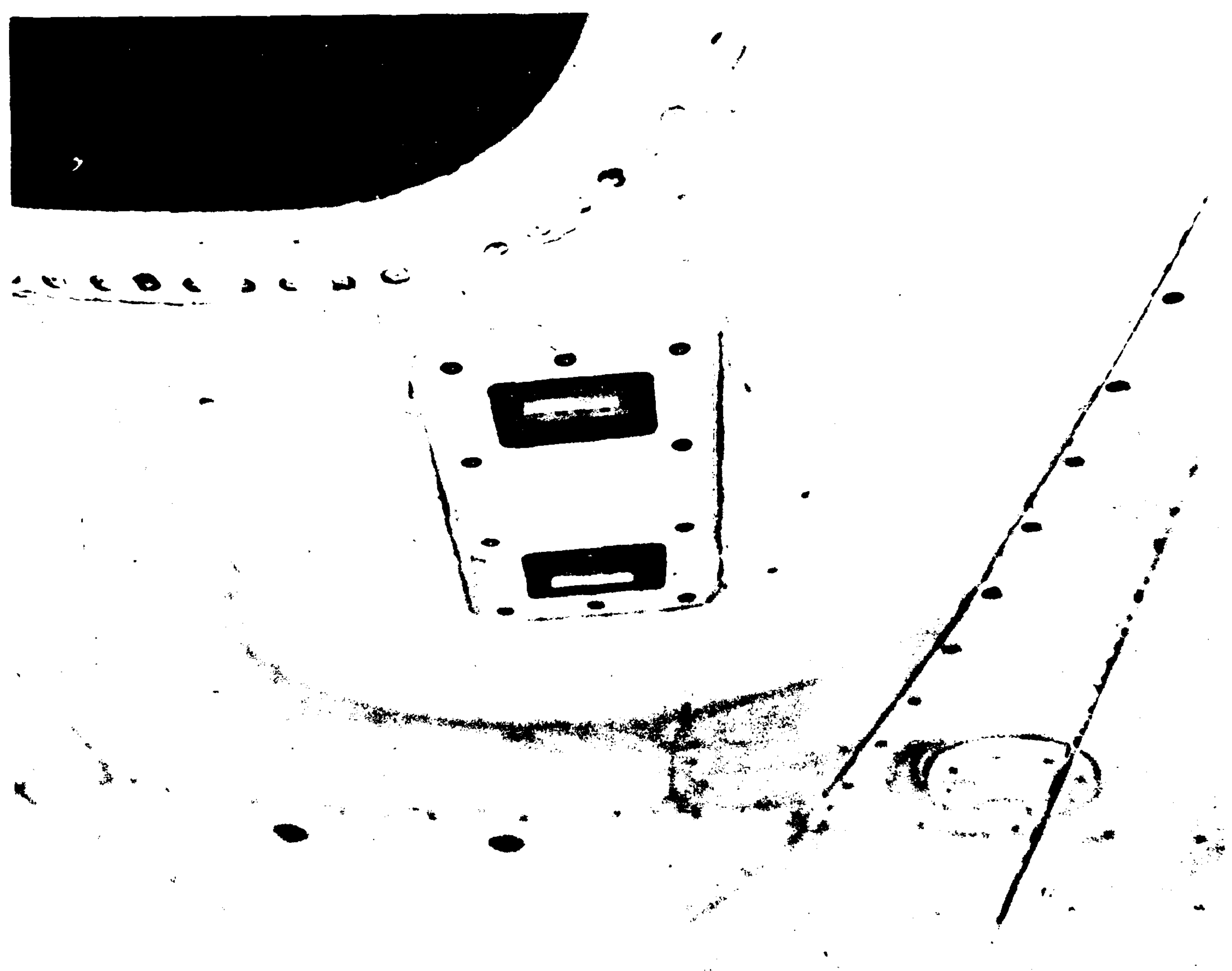

FIGURE 2. CORAN™ RECEIVING ANTENNA PAIR LOCATED AT FS 376.5 ON FUSELAGE UNDERSURFACE OF GULFSTREAM 1 AIRPLANE

frequency (PRF) is controlled by the processor to maximize the correlation between the front and rear receiving antenna outputs. When correlation approaches 100 percent, airplane groundspeed is computed by dividing the antenna separation distance by the time interval between the correlated antenna outputs.

CONTROL AND EXTERNAL INTERFACE. This unit provides the data interface between the CORAN™ and the pilot and/or external equipment. The interface provides:

1. Four-segment binary coded decimal (BCD) display (000.0 - 399.9) knots
2. Operator reset button (to initialize)
3. On-Off switch
4. Parallel output channel (14-bit latched velocity data)

The internal hardware is shown in figures 3 and 4.

SYSTEM CONCEPT.

The CORAN™ principle is based on the premise that the waveform of the ground-return signal from a radar is a unique function of the terrain characteristics, the position of the transmitting and receiving antennas with respect to the terrain, the transmitted pulse characteristics, and the antenna characteristics. If these are held constant, then the waveshape of the return signal is time-invariant. If all variables except the antenna system position are held constant, then the waveshape changes only as a function of that displacement. A small displacement causes a small change in return signal shape, and a larger displacement, a correspondingly larger change.

If two identical slightly displaced receiving antennas are moved such that their transmit-receive phase centers travel along the same path in space, then the waveforms observed will be very nearly identical, except that they will be displaced in time by an amount equal to the phase center separation distance divided by the velocity of the movement. Measurement of the time separation and knowledge of the phase center separation distance thus allows the velocity of the movement to be calculated. This is the principle upon which the CORAN™ system is based and is illustrated in figure 5.

VELOCITY MEASUREMENT. CORAN™ is a pulsed radar altimeter operating in the pulse width limited mode of operation, employing a transmit antenna plus a pair of physically displaced receive antennas as shown in figures 1 and 2. Figure 5 (part A) shows an aircraft, the aircraft antennas, and the rays to a few of the infinite number of random scatterers illuminated at any given instant.

Since the aircraft is moving, the phase of the ray to each scatterer is changing as a function of aircraft speed and the scatterer/antenna geometry. The result is a signal return which varies in amplitude and phase and has properties similar to narrowband noise. The received signals are not independent but are generally correlated depending on the geometry, terrain characteristics, and signal-return-to-receiver-noise ratio. If the antennas move so that their transmit-receive phase centers travel along the same line in space, and the reflected pulses are received alternately from each of the receiving antennas, then the envelopes of the received pulse trains, as noted, are very nearly identical. They are, however, displaced in time as shown in figure 5 (part B). Measurement of the time separation between them is accomplished by maximizing their cross-correlation by adjustment of the PRF so that a fixed number of pulses occur during the time required for the aft antenna phase center to move to the position occupied by the forward antenna phase center (about 2 to 3 milliseconds (ms) at typical approach speeds). With

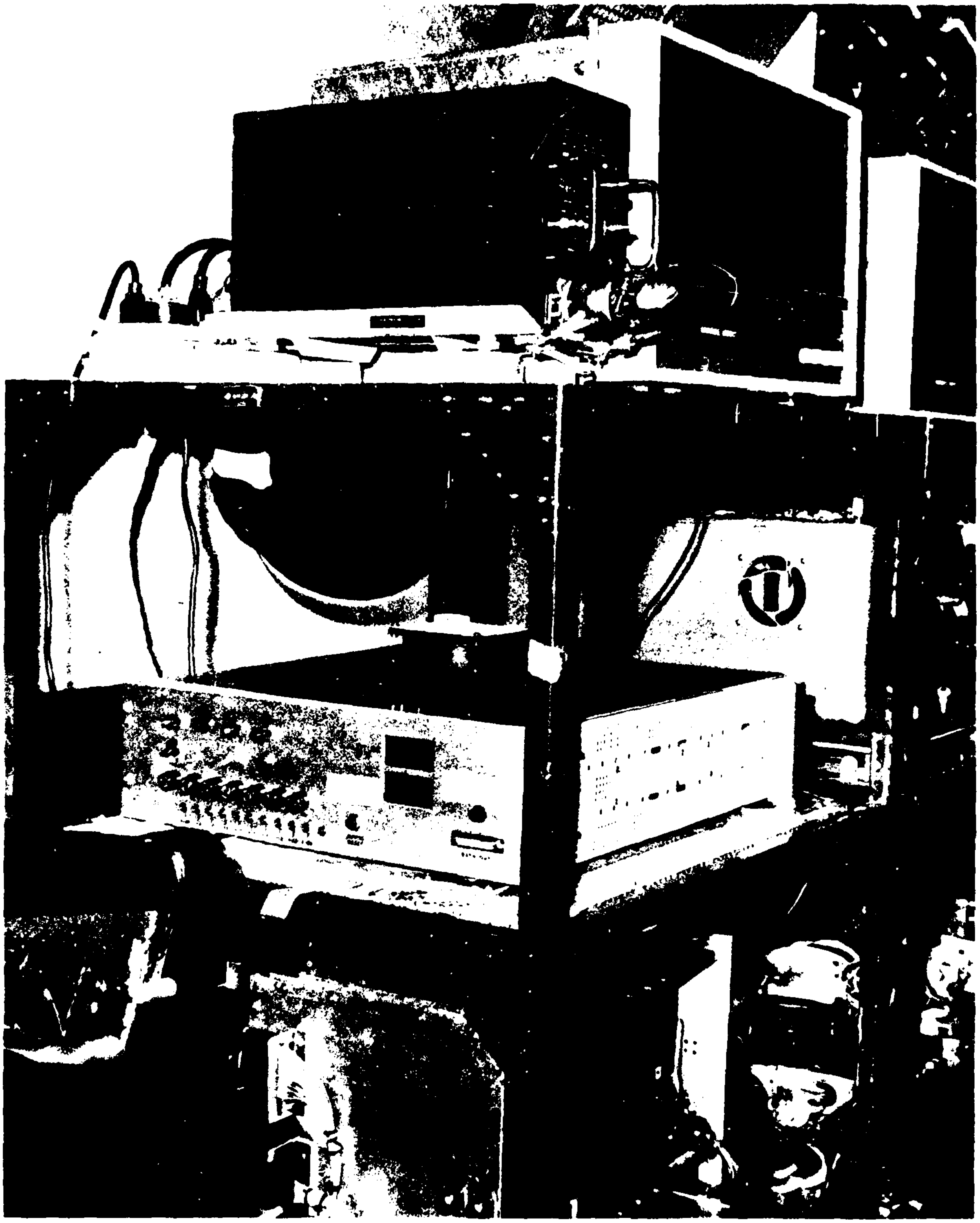

FIGURE 3. CORAN™ RACK INSTALLED IN GULFSTREAM I AIRPLANE

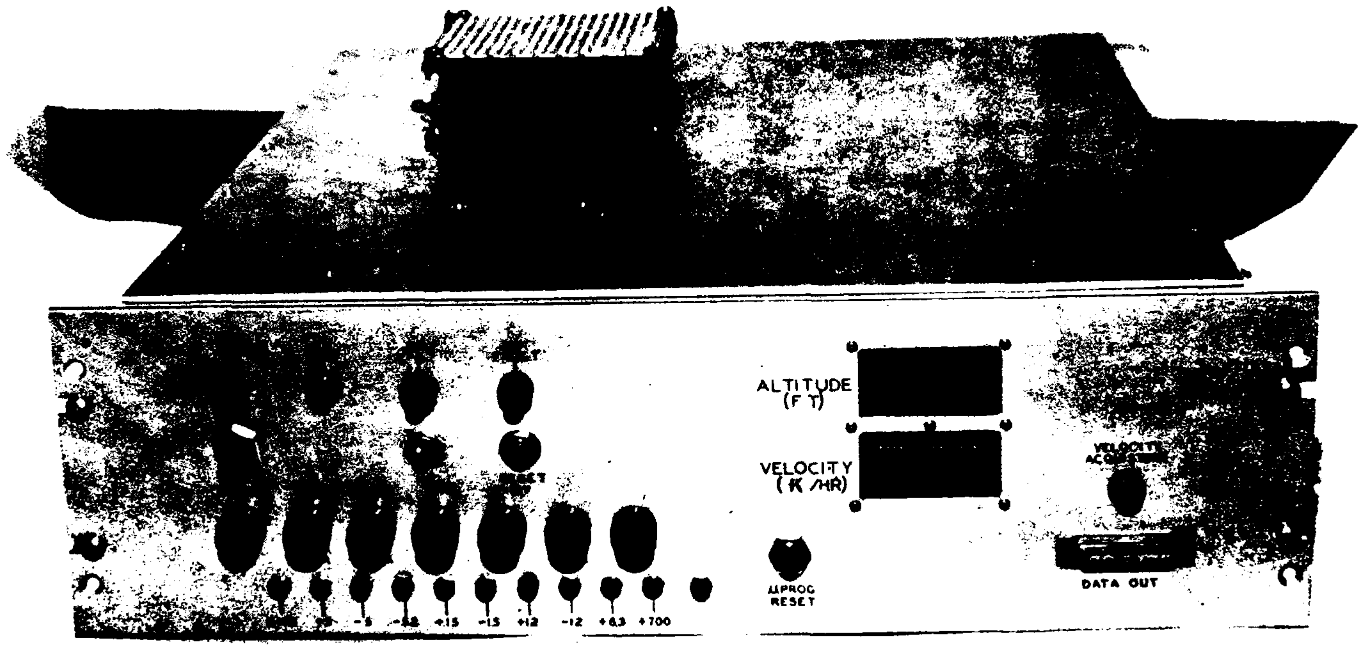

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FIGURE 4. CORAN™ POWER AND DISPLAY UNIT

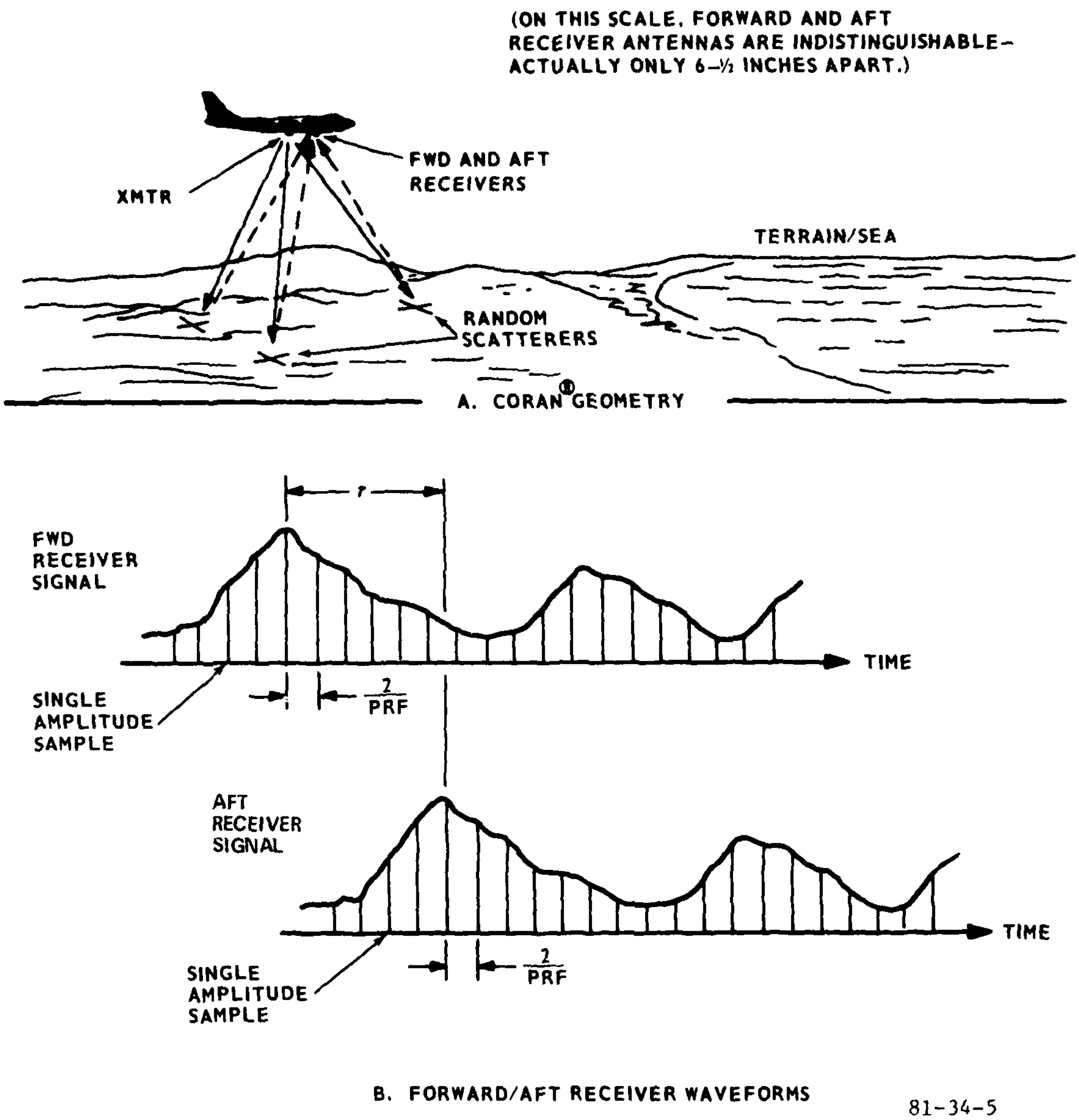


FIGURE 5. CORAN™ VELOCITY CONCEPT

a known phase center separation distance between fore and aft antennas, velocity is simply calculated as distance divided by time.

The basic velocity measurement quantities in the CORAN™ system are the PRF, which relates to the time delay between the forward and aft correlated returns, and the number of pulse repetition intervals (PRI) that occur before the aft antenna reaches the position previously occupied by the forward antenna. This number (N) is referred to as the algorithm number.

Figure 6 shows an antenna flight geometry with a drift angle Υ. If

d_c = Antenna forward/aft phase center separation,
N = Algorithm number,

then the distance that the airplane travels before a best correlation is made is

$$D = d_c \cos \Upsilon ,$$

and the time required for the airplane to traverse this distance is

$$T = N \cdot PRI.$$

Thus, the ground speed Vg = D/T becomes

$$Vg = \frac{d_c \cos\Upsilon}{N \cdot PRI}$$

$$= \frac{d_c}{N} PRF \cos\Upsilon$$

CORAN™ presents a fixed d_c and controls PRF and N to provide a correlation decision. The CORAN™ measurement of velocity is

$$V_m = \frac{d_c \times PRF}{N}$$

and by substitution,

$$V_m = \frac{V_g}{Cos}$$

For negligible drifts, the cosine of the drift angle is essentially 1, and

$$V_m \cong V_g$$

ATTITUDE SENSITIVITY. Since the CORAN™ concept uses the pulsewidth limited mode of operation, and since the antenna beam widths are relatively wide, the basic groundspeed and drift angle measurement techniques should be insensitive to airplane attitude.

It can be observed from figure 7 that the spot size or area illuminated by the altimeter is smaller than the antenna beam width as portrayed. As the airplane pitches and rolls, the same area is illuminated since it remains the point nearest the aircraft in altitude. It should be noted further that the tracking algorithms employed by the CORAN™ subsystem have been formulated to be insensitive to tracker-to-antenna gain variations, thus eliminating the need for critically matched antennas and ensuring good performance out to the beam edges during flight maneuvers.

While pitch and roll maneuvers do not affect the basic measurement processes, pitch attitude does effectively change the antenna baseline. To be strictly correct, a pitch angle input is required to transform the groundspeed from a body-centered coordinate system to a plane parallel to the ground. The effect of roll should be much less marked. For the normal range of pitch attitude during roll maneuvers, assuming that the antenna baseline is nearly parallel to the roll axis, the effect of roll attitude on groundspeed measurement should be negligible.

SYSTEM DESIGNED PERFORMANCE.

The test article has been produced for a concept demonstration test to be performed as part of the FAA's wind shear program. It has a design velocity range of 100 to 250 knots, an altitude range from 50 to 1,000 feet, and a performance goal of 3-percent velocity error with 1-second smoothing.

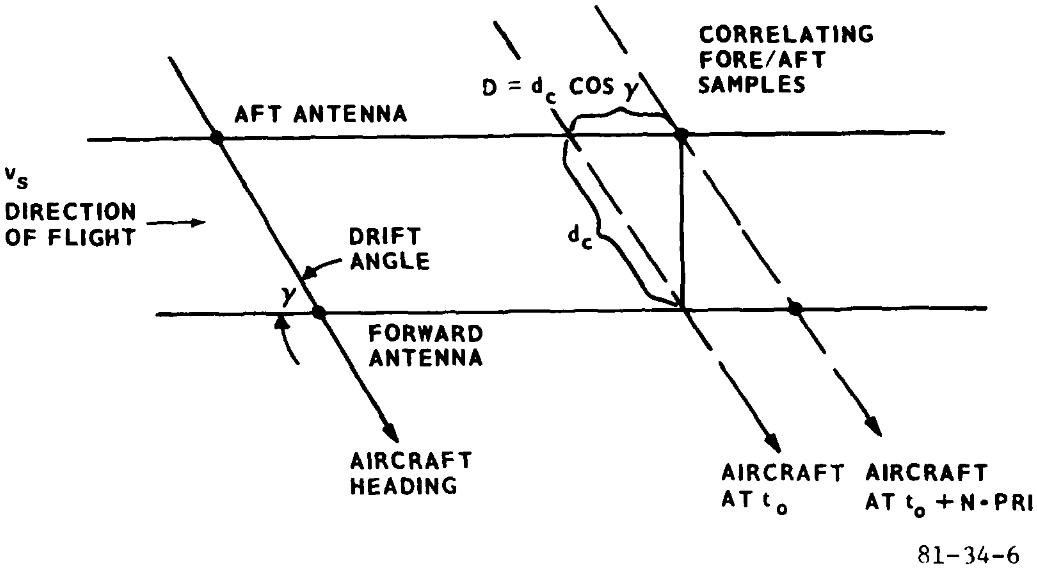


FIGURE 6. CORRELATION GEOMETRY IN A DRIFT

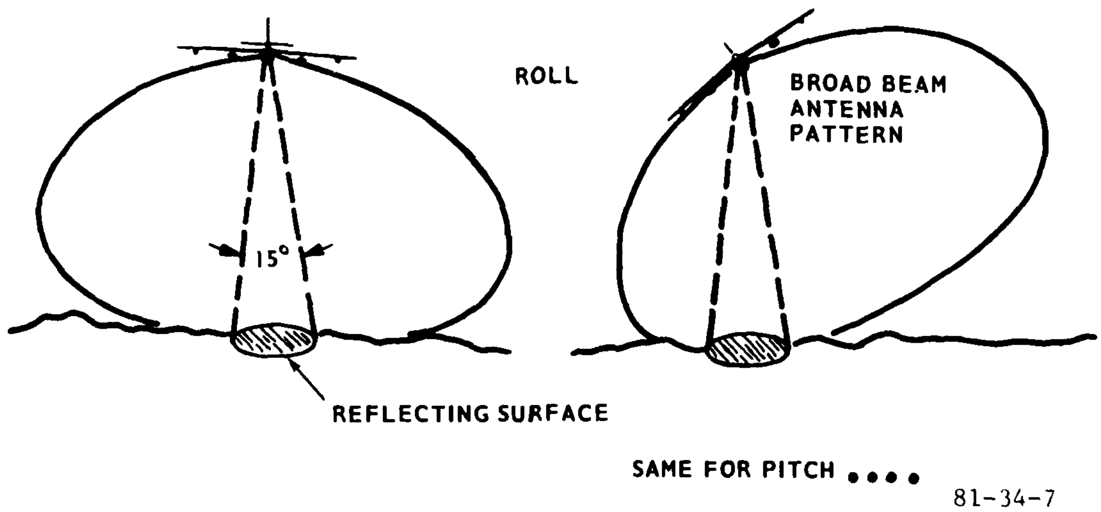


FIGURE 7. PITCH AND ROLL INSENSITIVITY

In designing a groundspeed system based on this concept, it is noted that performance at the upper altitude limit is determined by signal-to-noise ratio, which is controlled by peak power. Performance at the lower altitude limit is governed by the necessity to maintain pulse width limited operation.

The present system detects only the groundspeed component along the line between the phase centers of the forward antenna pair. It does not detect drift angle, and this precludes its use as a navigation system. For the measurement of groundspeed, however, on aircraft making a landing approach, the effect of drift is to foreshorten the antenna baseline by the cosine of the drift angle. At an airspeed of 140 knots, with a 90° crosswind of 30 knots, the true groundspeed would be 143.2 knots and the drift angle 12.1°. The uncorrected groundspeed would be 140 knots, in error by 2 percent. This is an extreme condition, to be sure, and in the majority of cases in which the wind was as high as 30 knots, the crosswind component would be less than the full 30 knots, and the groundspeed measurement error would be less than 2 percent. A 20 knot quartering wind (headwind or tailwind), for example, at 45° to the runway (14.14-knot crosswind) would result in an error of less than 1 knot.

While the measurement technique is supposed to be insensitive to airplane attitude, in the case of pitch displacement the effective longitudinal separation between the front and rear paired receiver antennas is foreshortened by the cosine of the pitch angle. This would amount to a 1.5-percent positive error at 10°. Since roll displacement does not foreshorten the antenna separation distance, no effect on groundspeed should be detected due to roll.

The manufacturer's flight tests of an earlier breadboard model indicated ability to perfom well over land, both clear and snow-covered, and over water, choppy or smooth. The groundspeed reference was an inertial platform of unspecified accuracy.

Mean errors were reported between 0.2 percent (for ocean with light chop) and 3 percent (smooth ocean).

TEST PROCEDURES.

Since the test article is a feasibility demonstration model only, a full range of tests over many different kinds of terrain was not conducted. Testing was confined to level flight at approximately 800 feet over relatively smooth inland water (Lake Oneida, New York) and the wooded lake shore. Airspeed was modulated as rapidly as possible to determine system responsiveness (which is more important than absolute steady-state accuracy). The results are summarized in figures B-1 through B-16 (appendix B) and table 1. Figures B-1 through B-8 present groundspeed measured by the CORAN™ and by the reference groundspeed unit as functions of time. Figures B-9 through B-16 present the difference between the two groundspeed measurements as a function of time. Statistical results are summarized in table 1.

TEST AIRPLANE. The test airplane was the FAA Technical Center Grumman Gulfstream 1 (N-47). It combined the desired characteristics of being reasonably economical to operate, providing sufficient room on the exterior for mounting the transmit and receive antennas far enough apart with the necessary optical isolation, and providing more than enough interior space for test equipment and personnel.

GROUNDSPEED REFERENCE. Reference groundspeed was provided by a Litton Industries LTN-51 Inertial Navigation System (INS) with an internal program selected to give 5 seconds of smoothing and a 1.4-second update time. A discussion of the INS accuracy is given in appendix C.

TABLE 1. CORAN™ STATISTICAL DATA

Run Number	Index	Flight Profile	CORAN™ V_h	INS V_h	ΔV_h	$\sigma\Delta V_h$	% NSD
1	230-570	Lake-Westbound (deceleration)	142.14	139.82	2.33	2.36	1.69
2	1,675-1,900	Lake-Eastbound (acceleration)	157.73	161.50	-3.76	3.74	2.32
3	2,185-2,545	Lake-Westbound (deceleration)	140.88	138.39	2.49	2.18	1.57
4	2,760-3,030	Land-Eastbound (accleration)	151.89	159.76	-7.87	2.00	1.25
5	3,100-3,500	Land-Westbound (deceleration)	142.34	146.53	-4.19	2.28	1.55
6	3,690-4,090	Lake-Eastbound (acceleration)	161.00	166.46	-5.45	4.41	2.64
7	4,280-4,650	Lake-Westbound (acceleration)	140.78	138.58	2.22	2.09	1.51
8	4,800-5,200	Lake-Eastbound	150.38	154.18	-3.80	2.81	1.82

Index = Time, seconds from start of record

$\overline{V}_h$ = Mean value of CORAN™ or INS groundspeed for run

$\Delta\overline{V}_h$ = $\overline{V}_h$ (CORAN™) - $\overline{V}_h$ (INS) mean difference = difference of means

$\sigma\Delta V_h$ = Standard deviation of (V_h(CORAN™) - $\overline{V}_h$(INS))

% NSD = Normalized standard deviation, ($\sigma \Delta V_h \times 100$) $\div$ ($\overline{V}_h$(INS))

RECORDING EQUIPMENT.

Data recording was limited to the groundspeed outputs of the subject and reference systems, CORAN™ altitude, CORAN™ AGC, and time. This information was recorded on a Kennedy 9800 9-track digital magnetic tape recorder. All variables were recorded once per second, which is quite sufficient for a transport category airplane in the flight conditions of interest in this test series.

RESULTS

Eight data runs were made, of which two (Nos. 4 and 5) were made over the wooded (and in places) heavily waterlogged lake shore. The rest were made over the surface of the lake. Winds were light and the chop on the lake surface was consequently very light. The INS output is a 5-second running average, updated approximately every 1.4 seconds. The CORAN™ output uses 1 second of smoothing, and for consistency in data presentation, it is plotted at the same update rate as the INS data.

Statistical summaries of each run's data are presented in table 1. The terms used in the summary are defined at the foot of the table. The quantity $\sigma \Delta V_h$ is the RMS of the variance (standard deviation) of the difference quantity (V_h (CORAN™) - V_h (INS)). The mean difference, $\Delta \overline{V}_h$, is larger than would be acceptable for an operational groundspeed system, particularly for the overland runs. Of more concern, however, is the spread in the mean difference between runs. The total spread between the largest positive mean difference and the largest negative is more than 10 knots. The normalized standard deviation is, in general, less than 2 percent of the mean INS groundspeed for a particular run.

While system accuracy is not acceptable (ideally, the mean difference with respect to the INS reference should not exceed 1 knot, with a standard deviation of 1 knot) at this stage of development, system responsiveness to fairly rapid changes in groundspeed (1 knot per second) is quite good. The difference plots show little or no change between the steady velocity sections of the record and the accelerating/decelerating sections.

Earlier flight test data provided by the manufacturer on a different system indicated that the radar return correlation system of measuring groundspeed is certainly capable of achieving the desired accuracy of performance with an acceptably small scatter in the data. The test article evaluated in the present report does not represent the optimum state of development or the state of development of the unit on which the earlier flight data were obtained.

Between data collecting runs over the lake and lake shore, the opportunity was taken to observe altitude and groundspeed measuring performance of the CORAN™ in turning flight. Time histories of system performance under these conditions were not recorded because it was not possible at the time to record pitch and roll angles with precision. It was noted, however, that altitude and groundspeed continued to be computed with little departure from their level flight values.

CONCLUSIONS

1. An accurate and responsive readout of airplane groundspeed in combination with airspeed has been shown to materially assist the pilot in executing an approach through a severe wind shear.

2. The CORAN™ feasibility demonstration unit displayed the ability to track rapidly varying groundspeed in level flight and to continue tracking during turning, climbing, and descending flight.

3. As presently configured, the unit does not consistently produce the required accuracy (3-knot velocity differential with respect to the reference inertial navigation system). However, system performance on certain runs approached the required accuracy.

4. Noise in the data (part of which is attributable to the reference inertial navigation system) as measured by the normalized standard deviation of the groundspeed differential; i.e., ($V_{h_{CORAN™}} - V_{h_{INS}}$) is between 1.5 percent and 2.5 percent of the mean reference groundspeed for the run in question.

REFERENCES

1. Gastrer, W.S., and Foy, W.A., Piloted Simulation Study of Low-Level Wind Shear, Phase 4, report under Contract DOT-FA75WA-3650, U. S. Department of Transportation (DOT), FAA, Stanford Research Institute International, Menlo Park, California, March 1979.

2. Kelley, W. W., Simulation Study to Evaluate a Constant Groundspeed Approach Method in Moderate and Severe Wind Shears, NASA TM 80060, NASA Langley Research Center, Hampton, Virginia, March 1978.

3. Abzug, M. J., Airspeed Stability under Wind Shear Conditions, Engineering Notes, Journal of Aircraft (AIAA), Volume 14, No. 3, March 1977.

APPENDIX A

Airplane Response to a Longitudinal Gust.

The Laplace transfer function for airplane longitudinal response to a head-on gust is

$$\bar{u} = \frac{2\,\mu(2\,\mu s - C_{z_\alpha})\,\hat{u}(o)}{(2\,\mu s - C_{x_u})\,(2\,\mu s - C_{z_\alpha}) + C_{x_\alpha}(2C_{L_o} - C_{z_u})} \qquad \text{(A-1)}$$

Inserting figures for a typical 4-engine jet transport airplane in approach configuration, at an indicated airspeed of 148 knots:

$$\bar{u} = \frac{(s + 0.0282)\,\hat{u}(o)}{(s + 0.0274)(s + 0.0018)} \qquad \text{(A-2)}$$

where: $\bar{u}$ = Laplace Transform of $\hat{u}$
$\hat{u}$ = Normalized disturbance velocity
$\hat{u}(o)$ = Normalized step (gust) input

$\mu = 86.62$	$C_{x_\alpha} = 0.35$
$C_{z_\alpha} = -4.89$	$C_{L_o} = 0.900$
$C_{x_u} = -0.175$	$C_{z_u} \cong 0$

μ = Airplane relative density coefficient
C_{z_α} = Vertical force — angle of attack derivative
C_{x_u} = Speed damping derivative
C_{x_α} = Longitudinal force — angle of attack derivative
C_{L_o} = Steady-state lift coefficient
C_{z_u} = Vertical force — speed derivative (≈ 0 in low subsonic flight)

It is assumed that during the time of the response, airplane attitude is held constant and that no thrust adjustment is made. Neither is there any change in landing gear or flap position.

In equation (A-2), the zero at s = -0.0282 is nearly cancelled by the pole at s = -0.0274, so that with very little approximation, (2) can be written

$$\bar{u} = \frac{\hat{u}(0)}{s + 0.0018} \qquad \text{(A-3)}$$

or

$$\hat{u}(\hat{t}) \approx u(0)e^{-0.0018\hat{t}}, \text{ for } \hat{u}(0) = \text{Constant}$$

where:

$$\hat{t} = t \div t^*$$

$$t^* = c \div 2u_0$$

Equation (A-3) is in nondimensional time, and the final form, in natural time is

$$u(t) = u(0)e^{-0.045t} \qquad \text{(A-4)}$$

This is a first-order response with a time constant λ = 22.2s. After four time constants, the disturbed motion of a system subjected to a step input is essentially complete. In this instance, it would mean that the airplane would regain its original equilibrium state in about 90 seconds.

The corresponding transfer function for airplane angle-of-attack is

$$\bar{\alpha} = \frac{-0.0104\ \hat{u}(0)}{(s + 0.0274)\ (s + 0.0018)} \qquad \text{(A-5)}$$

or

$$\alpha(t) = 0.406\hat{u}(0)\left(e^{-0.685t} - e^{-0.045t}\right) \qquad \text{(A-6)}$$

Equation (A-6) indicates a negative initial response in $\alpha(t)$ to a positive u(o). The first observable change occurring after an airplane is hit by a head-on gust is, in fact, a reduction in *angle-of-attack, since if the attitude is held constant* as the airplane rises because of the rapid increase in lift, the angle of attack is reduced proportionally to the vertical velocity induced by the gust. The altitude loss associated with a negative instantaneous gust can readily be calculated. The rate of descent/climb is given by:

$$\dot{h} = -u\alpha$$

where $u = u_0 + u(0)e^{-0.045t}$

and $\alpha = 0.406\hat{u}(0)\left(e^{-0.685t} - e^{-0.045t}\right)$

Inserting typical values (u_0 = 250 ft/s^{-1}, $u(0) = -0.1u_0$)

$$\dot{h} = 10.15\left(e^{-0.685t} - e^{-0.045t} - 0.1e^{-0.730t} + 0.1e^{-0.090t}\right)$$

and

$$\Delta h = \left(-\ 14.819e^{-0.685t} + 225.553e^{-0.045t} + 1.391e^{-0.730t} - 11.277e^{-0.090t}\right)$$

The time histories of $u(t)$, $\alpha(t)$, $h(t)$ and $\dot{h}(t)$ have been calculated and are plotted in figure A-1. The final value for Δh is -201 feet (ft). A rough estimate of Δh can also be made purely from energy considerations.

$$\Delta h = \frac{V_1^2 - V_2^2}{2g}$$

where:

V_1 = Initial airspeed, ft/s

V_2 = Initial airspeed minus gust velocity.

Inserting:

V_1 = 250 ft/s

V_2 = 225 ft/s

Δh = 185 ft.

The difference between the two results is due to the work done against drag, which is accounted for in the integration of the rate of climb/descent equation, but is not accounted for in the simple energy exchange calculation.

	Definition of Symbols	Units
$\bar{c}$	Airplane mean aerodynamic chord	ft
C_{L_o}	Steady state lift coefficient	
C_{x_u}	Speed damping derivative	
C_{x_α}	Longitudinal — angle-of-attack derivative	
C_{z_u}	Lift-speed derivative	
C_{z_α}	Lift-angle-of-attack derivative	
g	Acceleration due to gravity	ft/s^2
$\dot{h}$	Rate of climb	ft/s
Δh	Altitude increment	ft
s	Laplace operator	
t	Time	s
$\hat{t}$	Nondimensional time	

Definition of Symbols		Units
t^*	Normalizing factor for time	s
u	Disturbance velocity (longitudinal)	ft/s
$\hat{u}$	Nondimensional disturbance velocity	
$\bar{u}$	Laplace Transform of u	
$\hat{u}(0)$	Initial value of u	
u_0	Steady-state airspeed	ft/s
$u(0)$	Initial value of u	ft/s
α	Angle of attack (disturbance value)	radians
$\bar{\alpha}$	Laplace Transform of α	
μ	Airplane relative density coefficient	
λ	Time constant	s

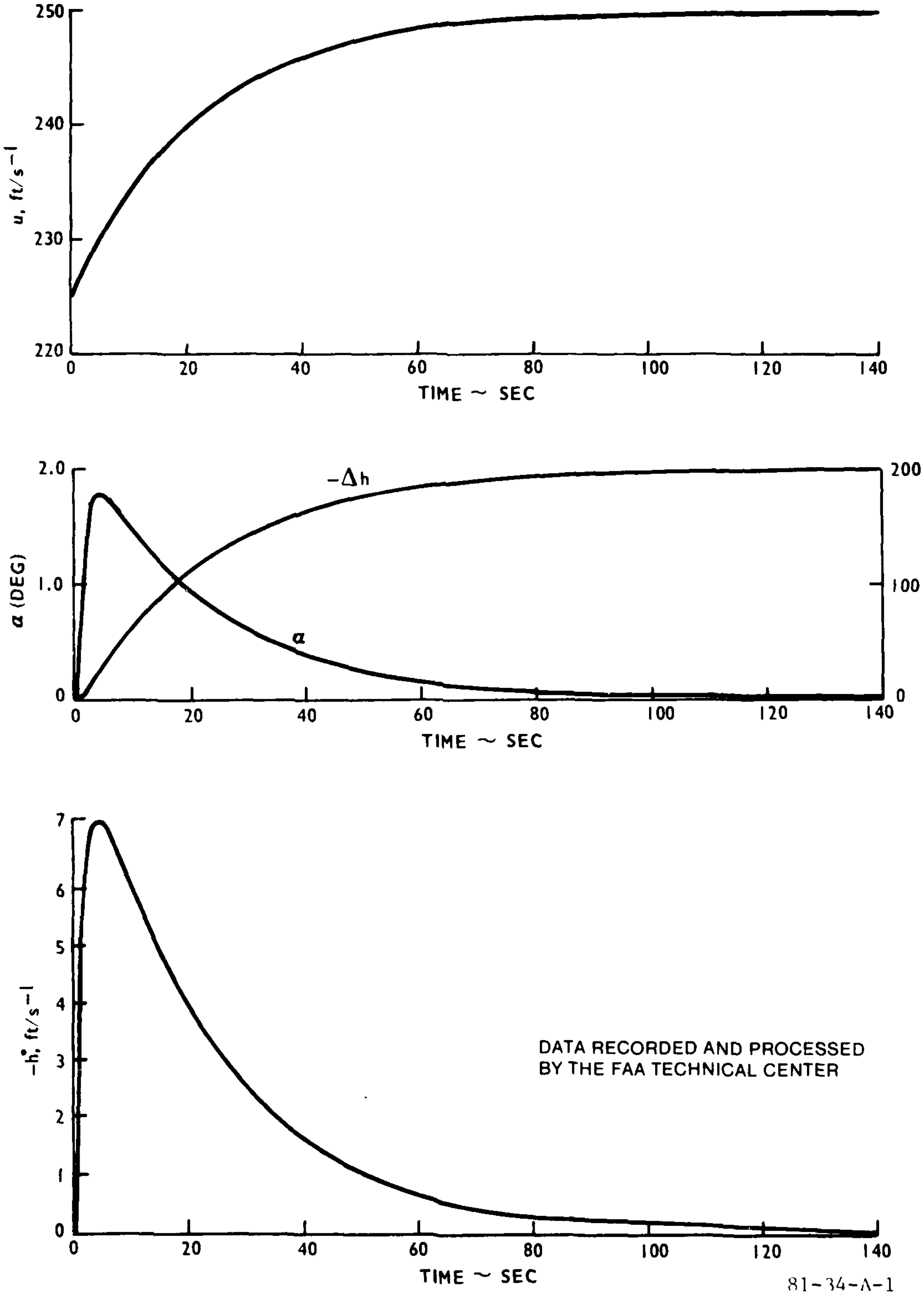


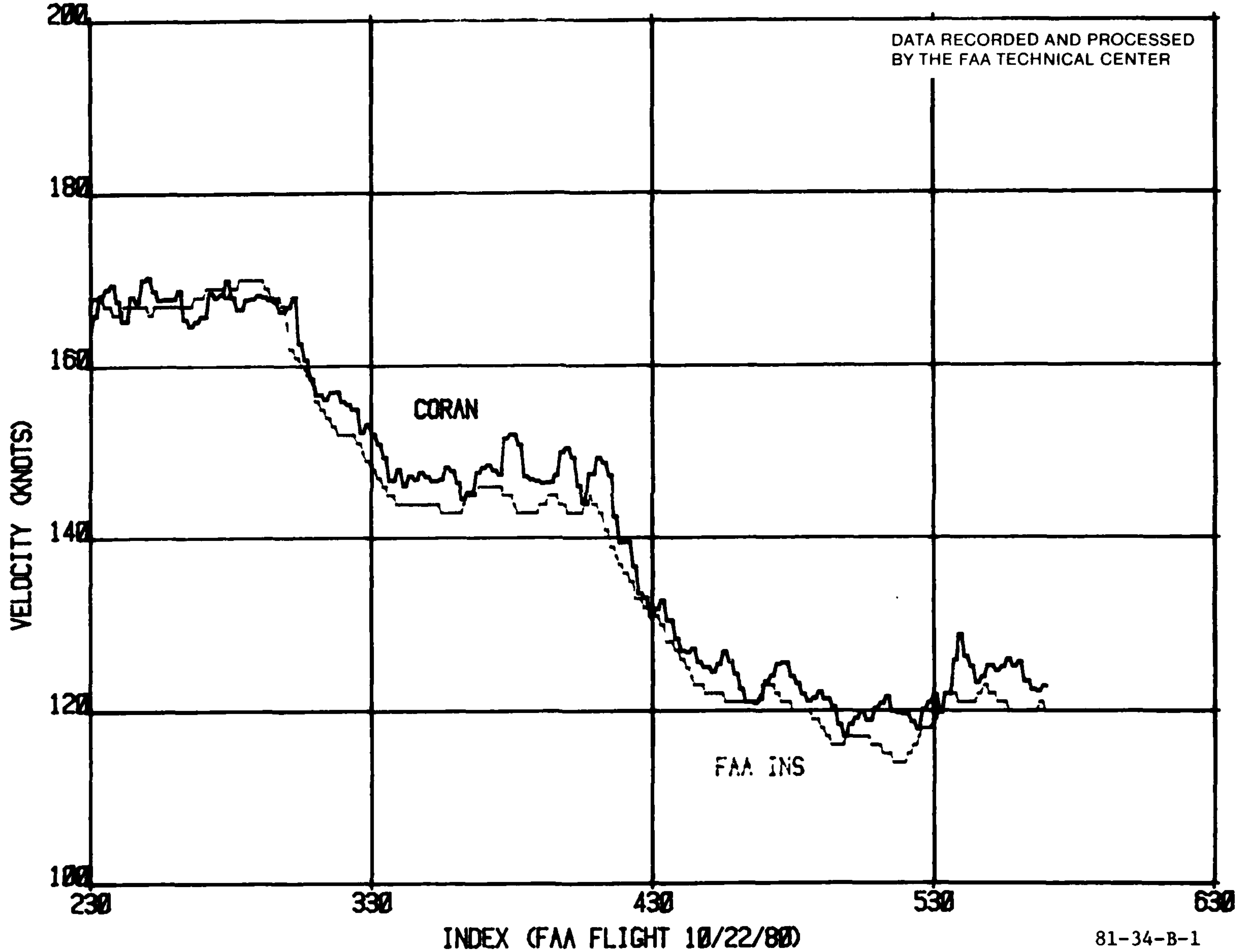
FIGURE A-1. TIME HISTORIES

APPENDIX B

Results

This appendix presents (1) time histories of the groundspeed outputs of the test article and of the reference Inertial Navigation System (INS) and (2) time histories of the difference between the two ground speeds. These data are summarized in table 1 CORAN™ Statistical Data.

LIST OF ILLUSTRATIONS



81-34-B-1

FIGURE B-1. VELOCITY TIME HISTORY; (IN SECONDS) RUN 1, OVER WATER

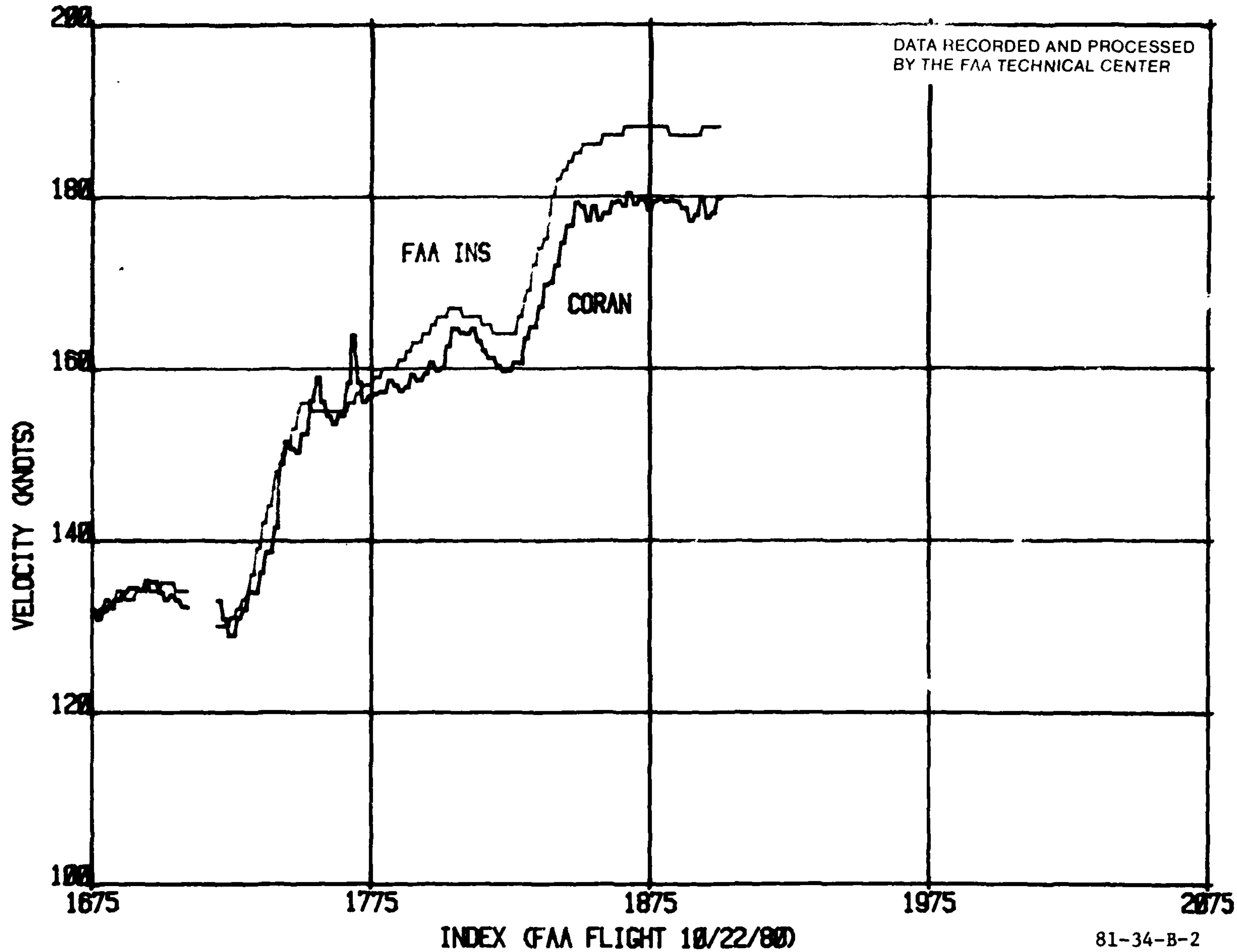


FIGURE B-2. VELOCITY TIME HISTORY; (IN SECONDS) RUN 2, OVER WATER

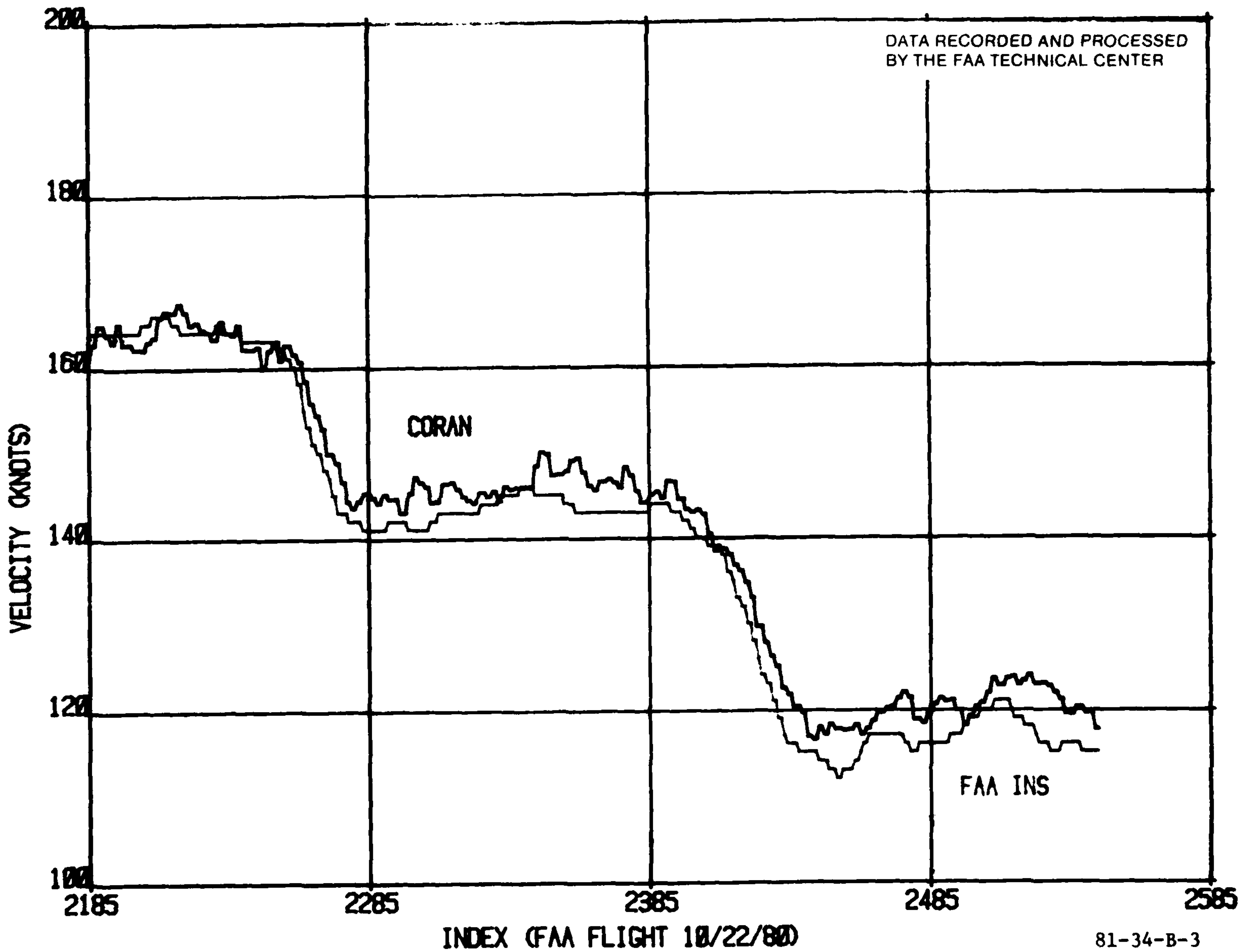


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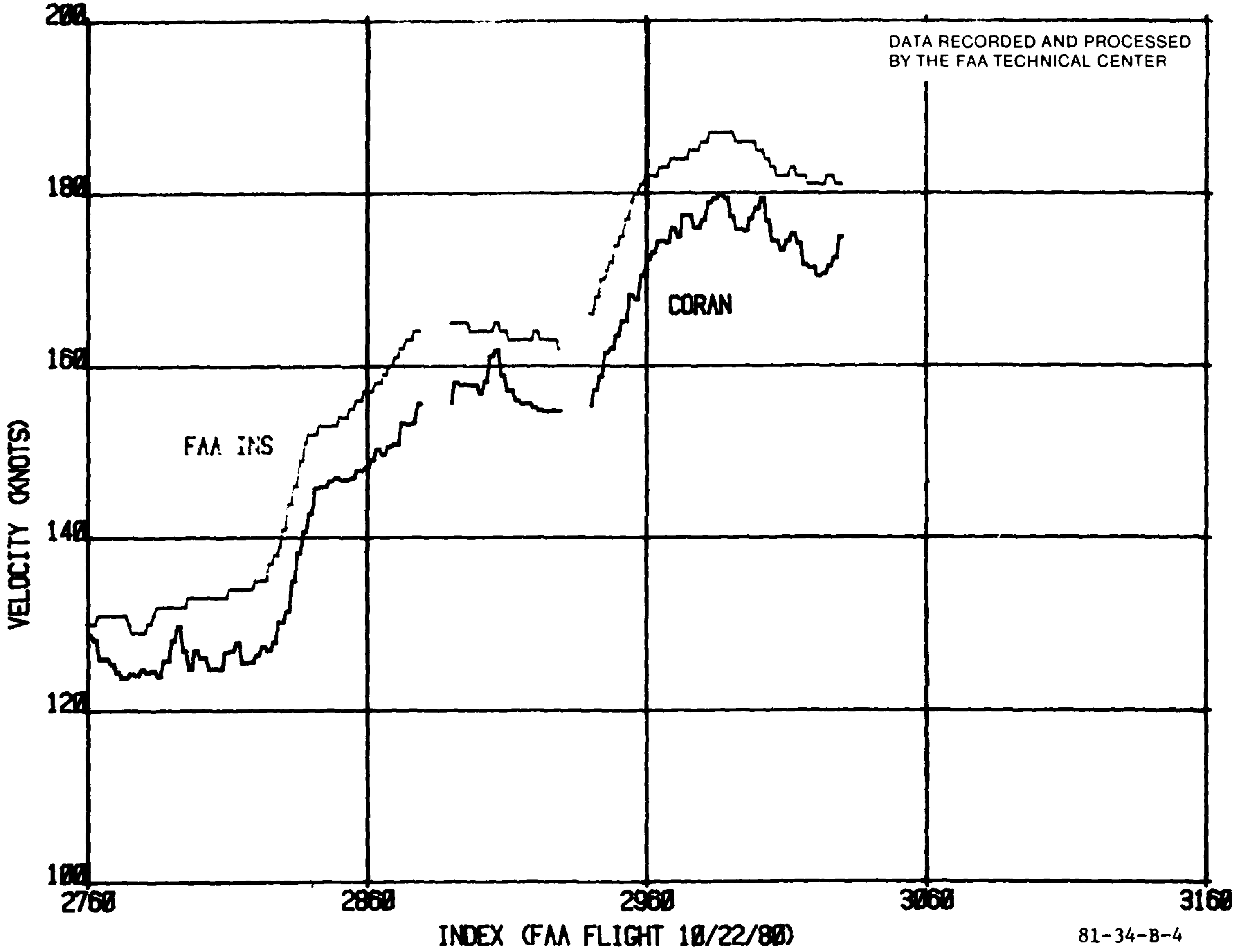
FIGURE B-3. VELOCITY TIME HISTORY; (IN SECONDS) RUN 3, OVER WATER



81-34-B-4

FIGURE B-4. VELOCITY TIME HISTORY; (IN SECONDS) RUN 4, OVER LAND

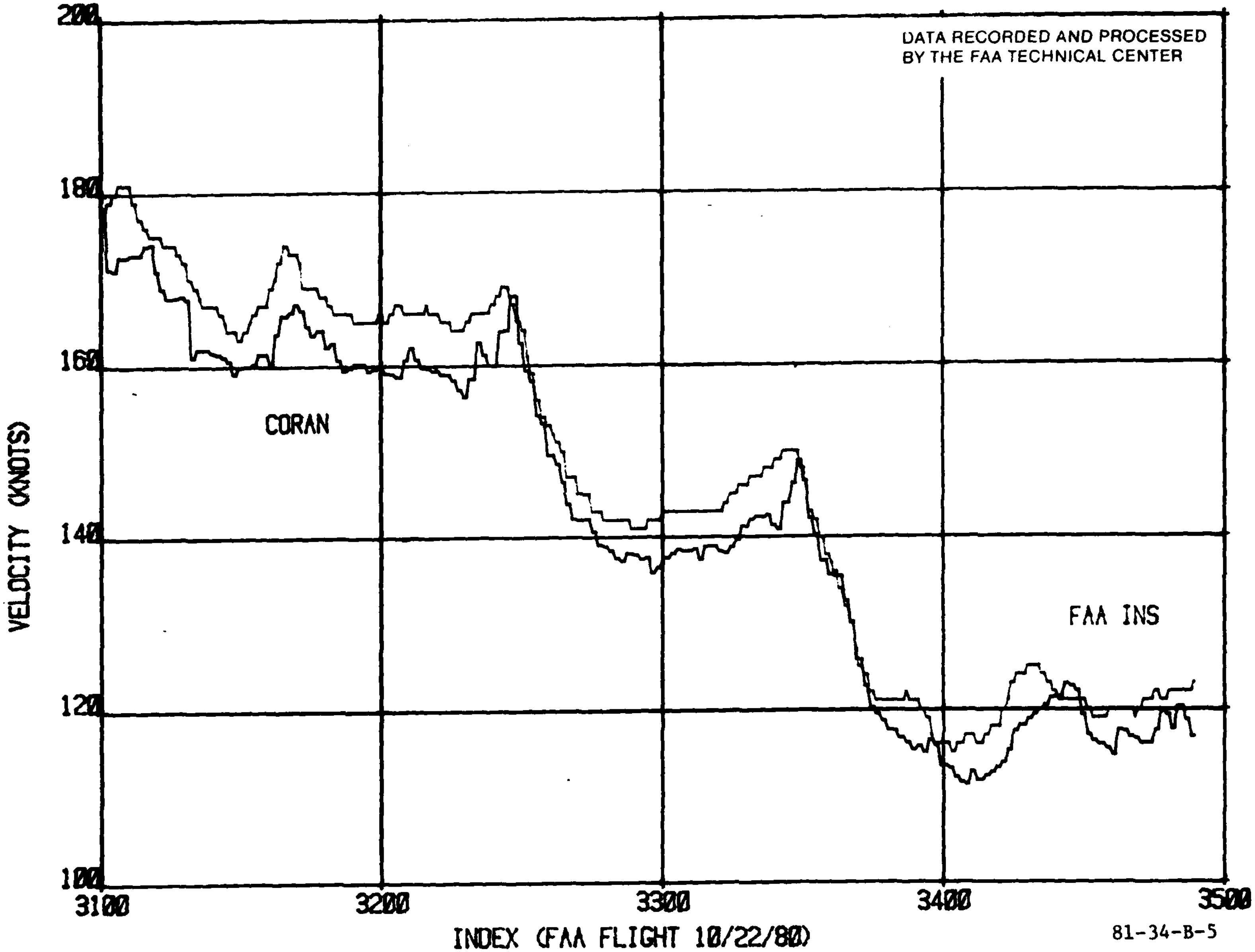


FIGURE B-5. VELOCITY TIME HISTORY; (IN SECONDS) RUN 5, OVER LAND

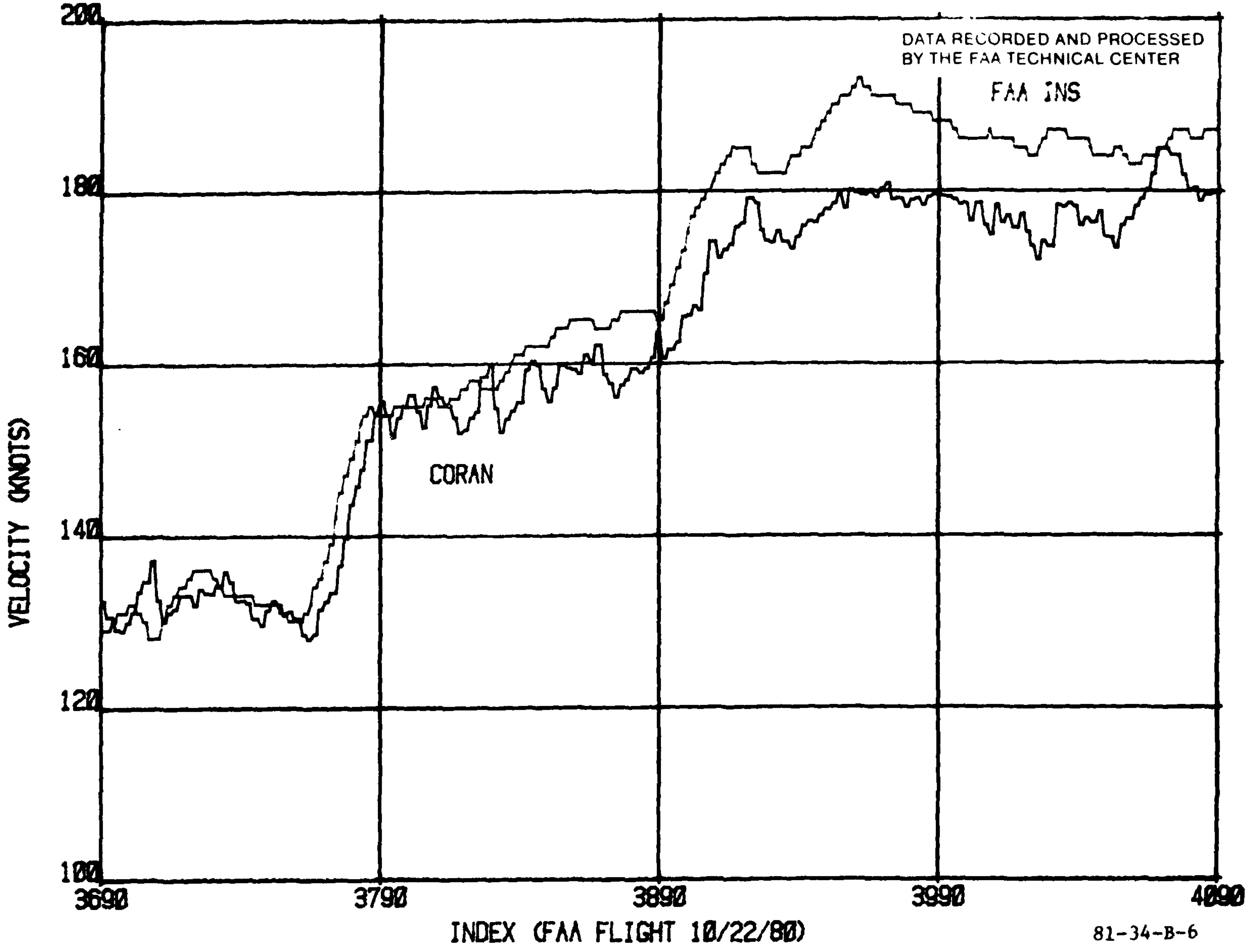


FIGURE B-6. VELOCITY TIME HISTORY; (IN SECONDS) RUN 6, OVER WATER

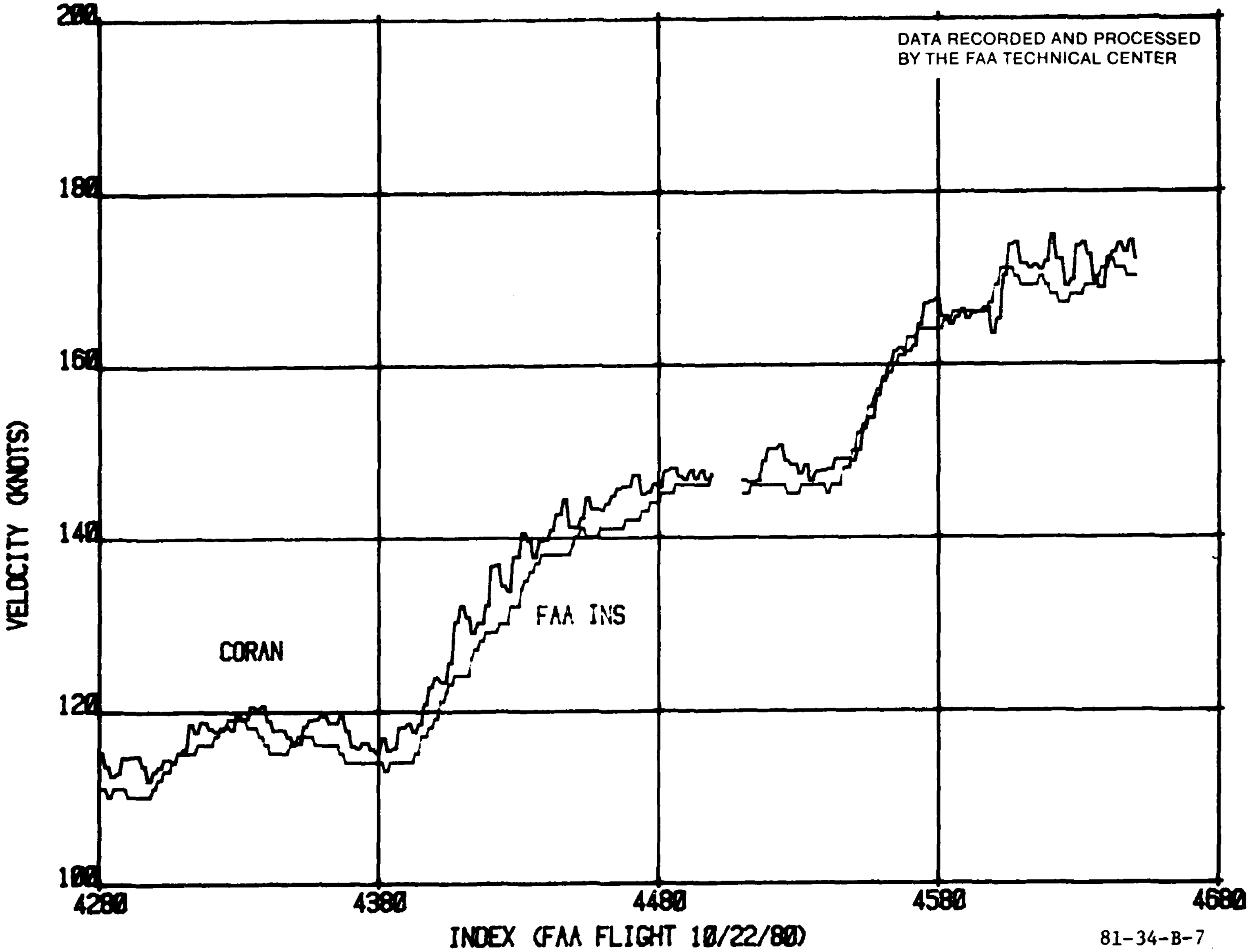


FIGURE B-7. VELOCITY TIME HISTORY; (IN SECONDS) RUN 7, OVER WATER

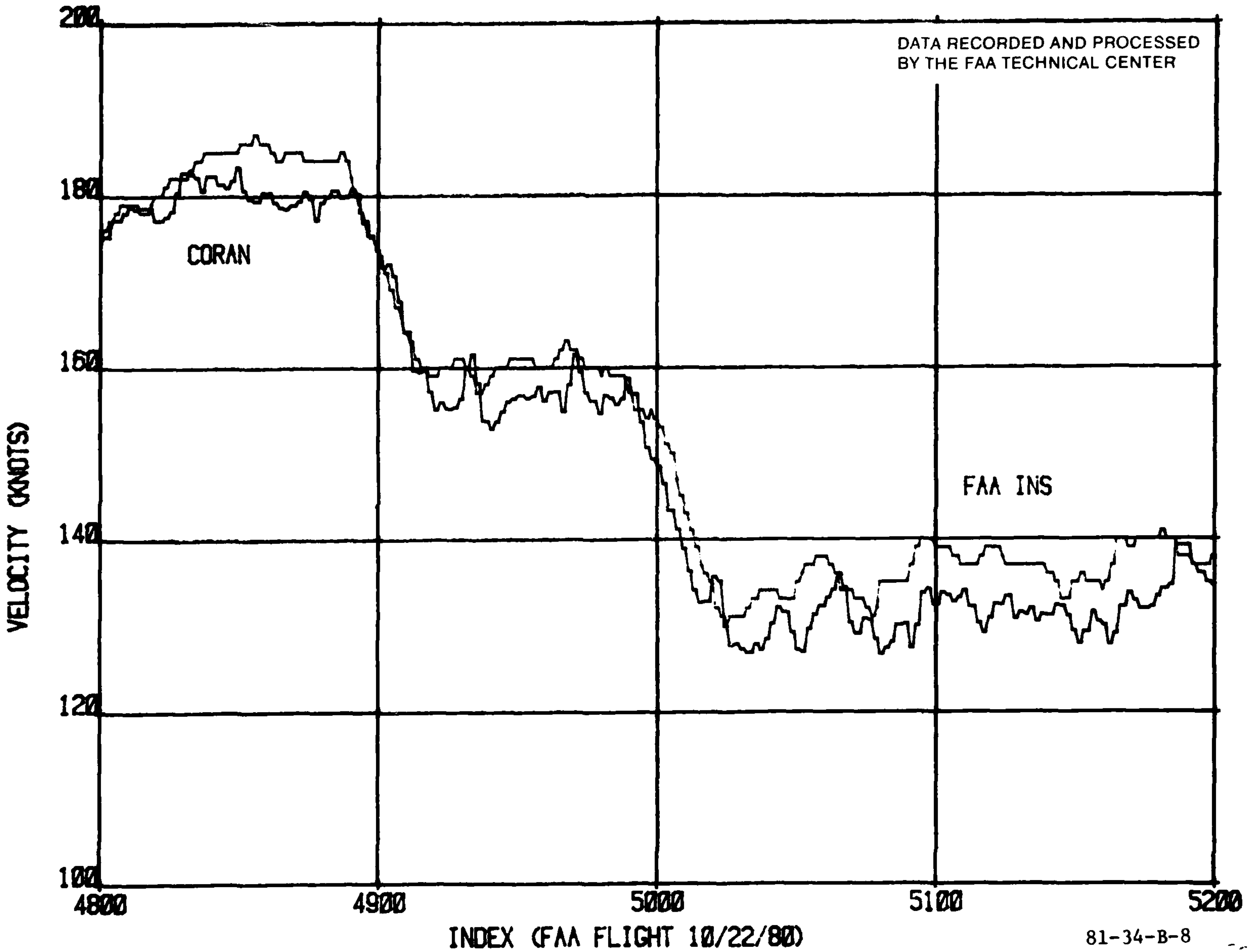
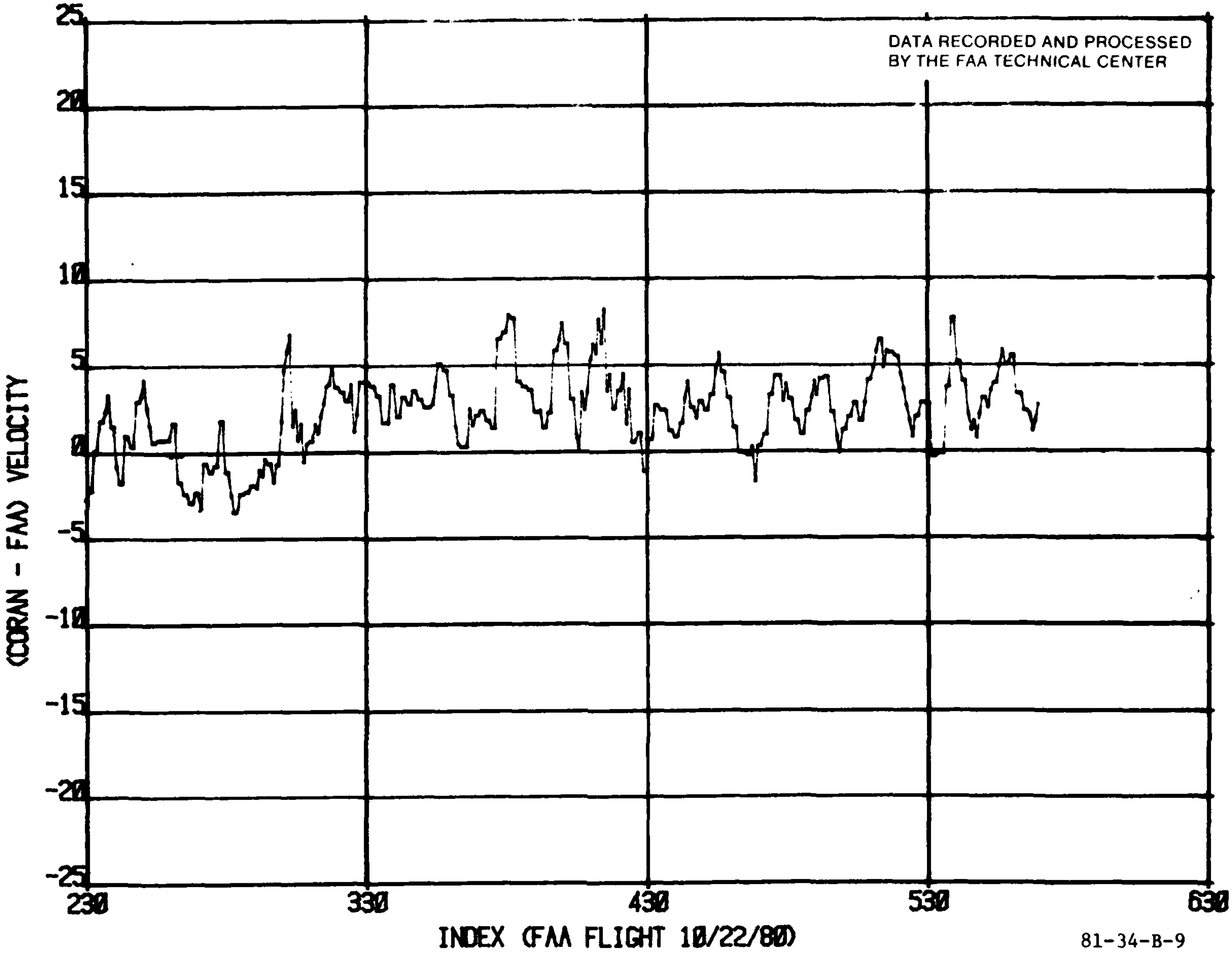
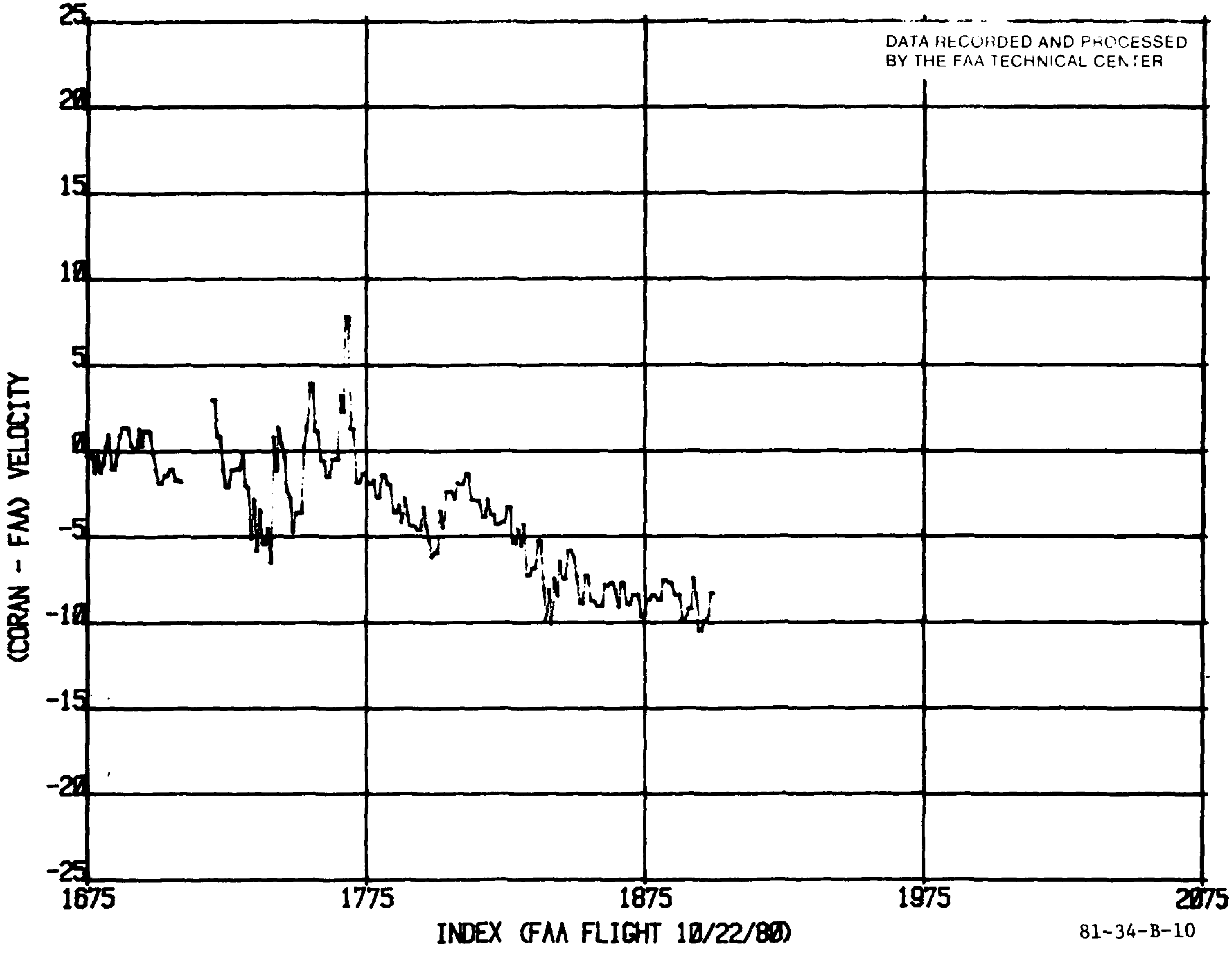


FIGURE B-8. VELOCITY TIME HISTORY; (IN SECONDS) RUN 8, OVER WATER



81-34-B-9

FIGURE B-9. VELOCITY DIFFERENCE; (IN SECONDS) (CORAN™-INS) RUN 8, OVER WATER



81-34-B-10

FIGURE B-10. VELOCITY DIFFERENCE; (IN SECONDS) (CORAN™-INS) RUN 2, OVER WATER

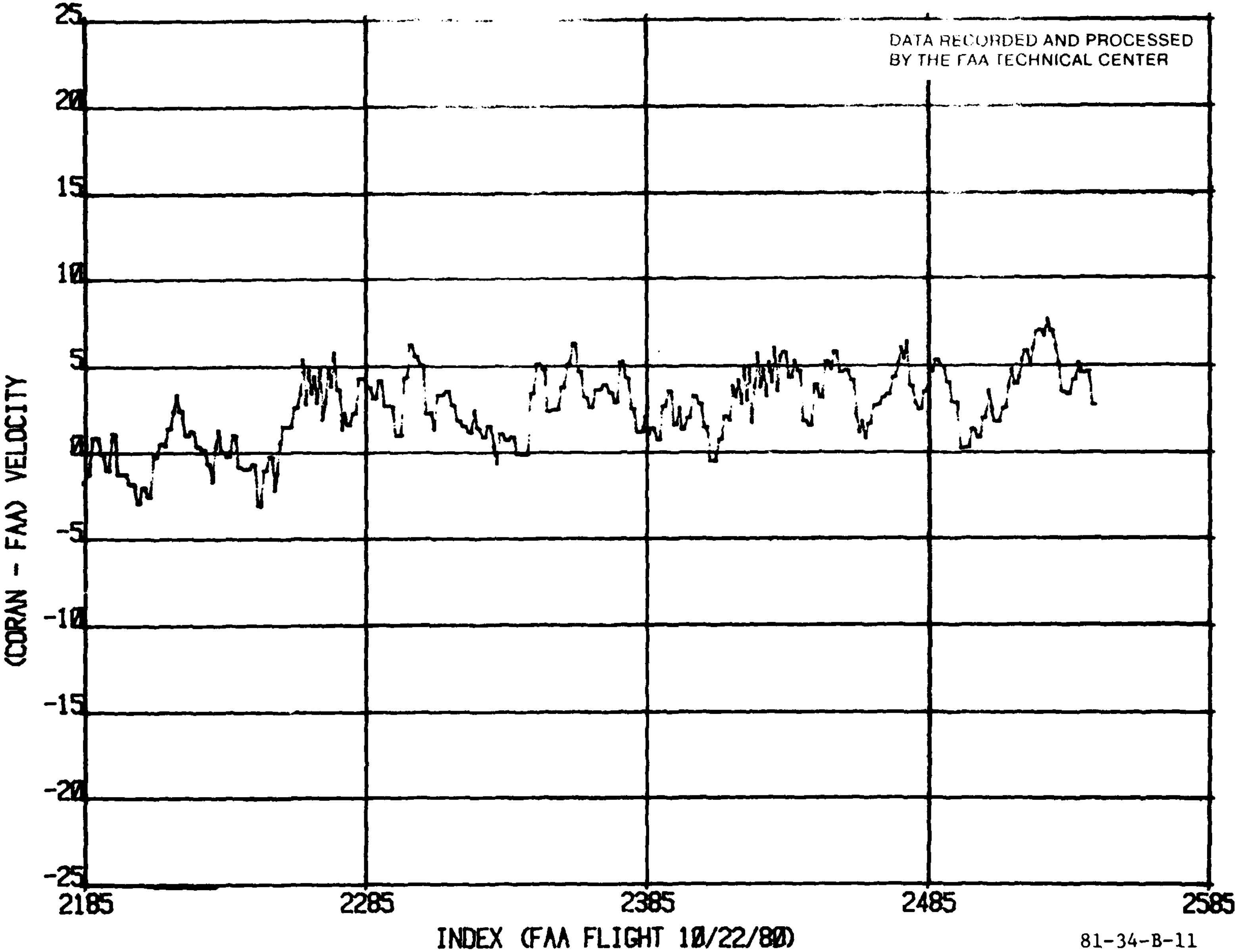
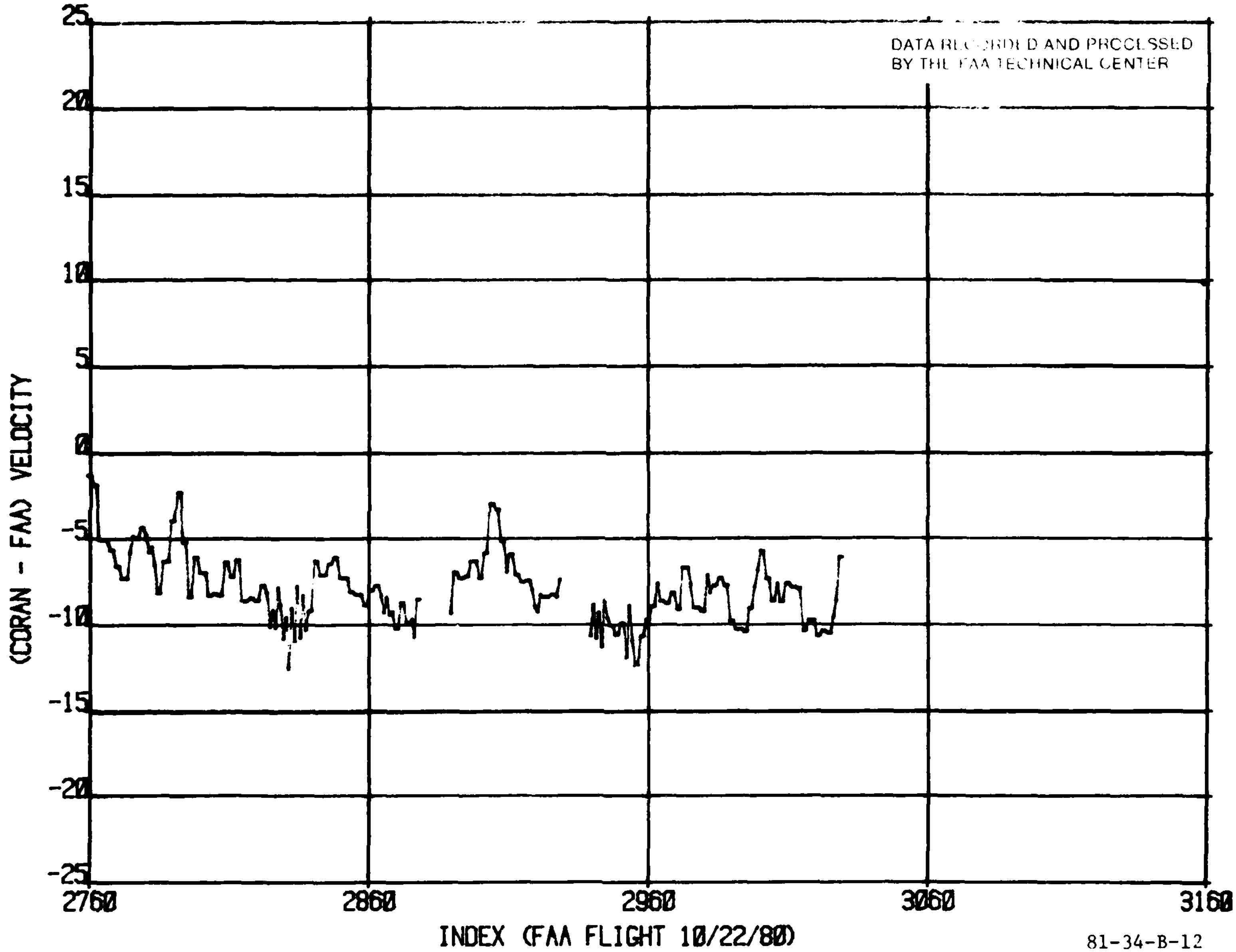
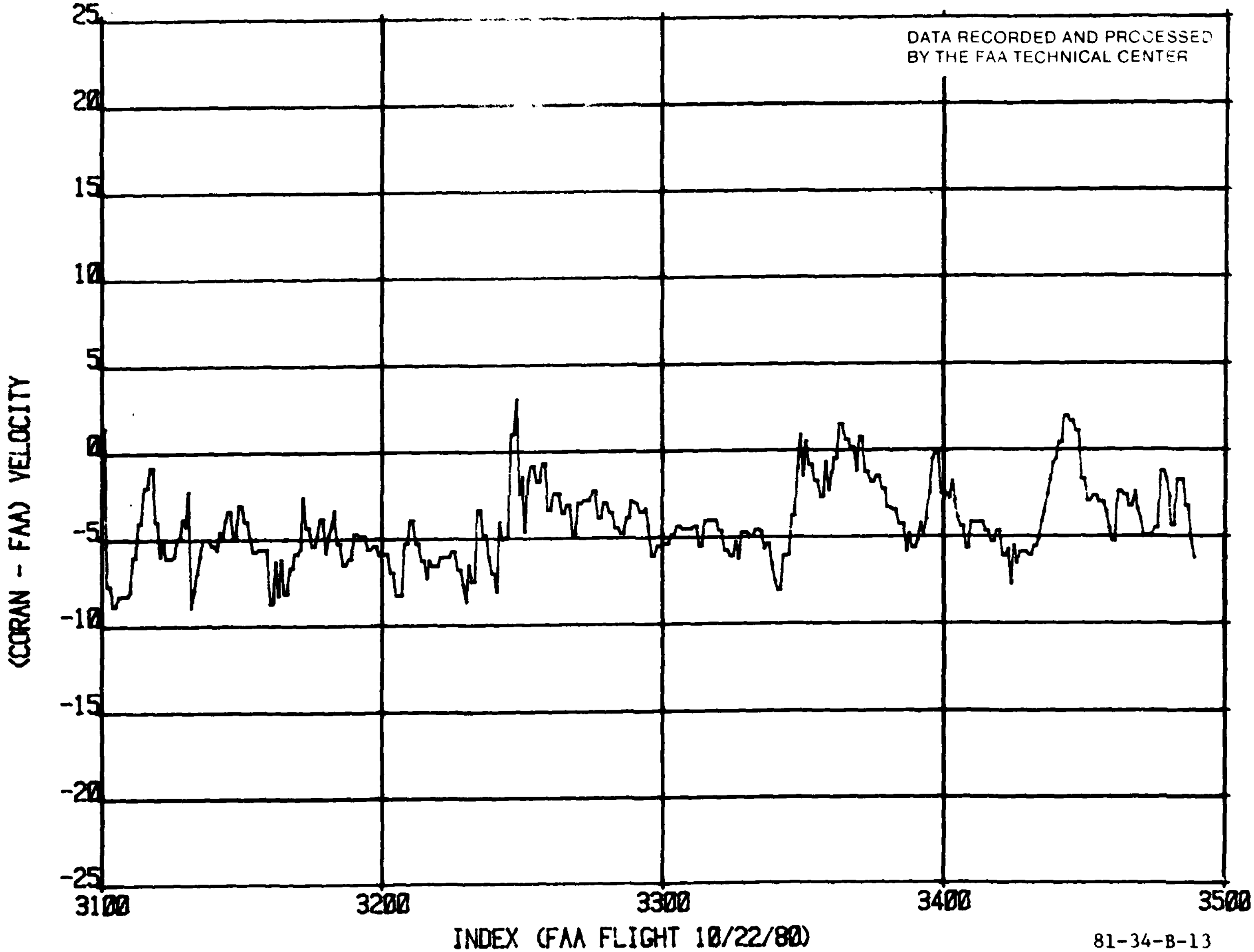


FIGURE B-11. VELOCITY DIFFERENCE; (CORAN™-INS) RUN 3, OVER WATER



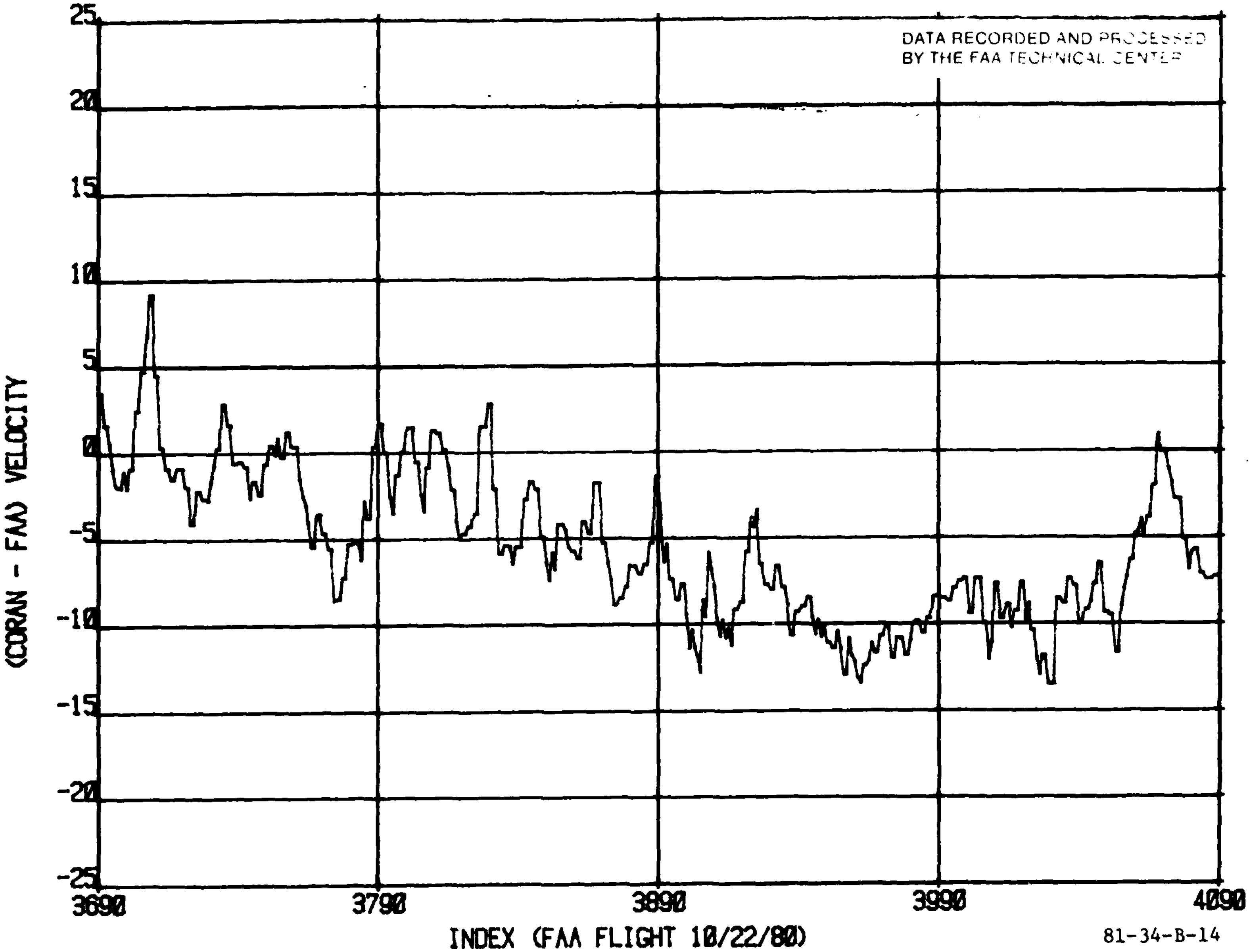
81-34-B-12

FIGURE B-12. VELOCITY DIFFERENCE; (CORAN™-INS) RUN 4, OVER WATER



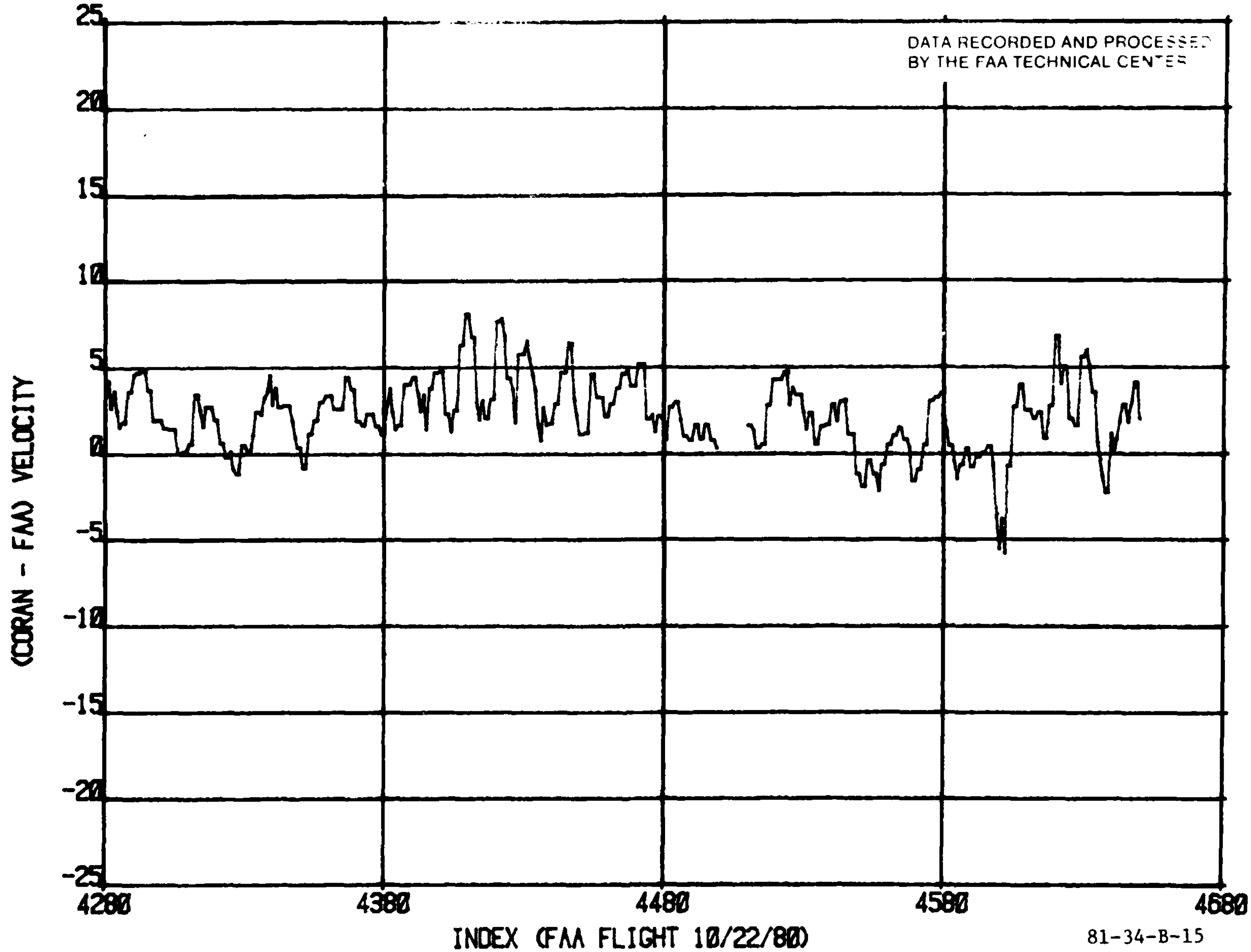
81-34-B-13

FIGURE B-13. VELOCITY DIFFERENCE; (CORAN™-INS) RUN 5, OVER WATER



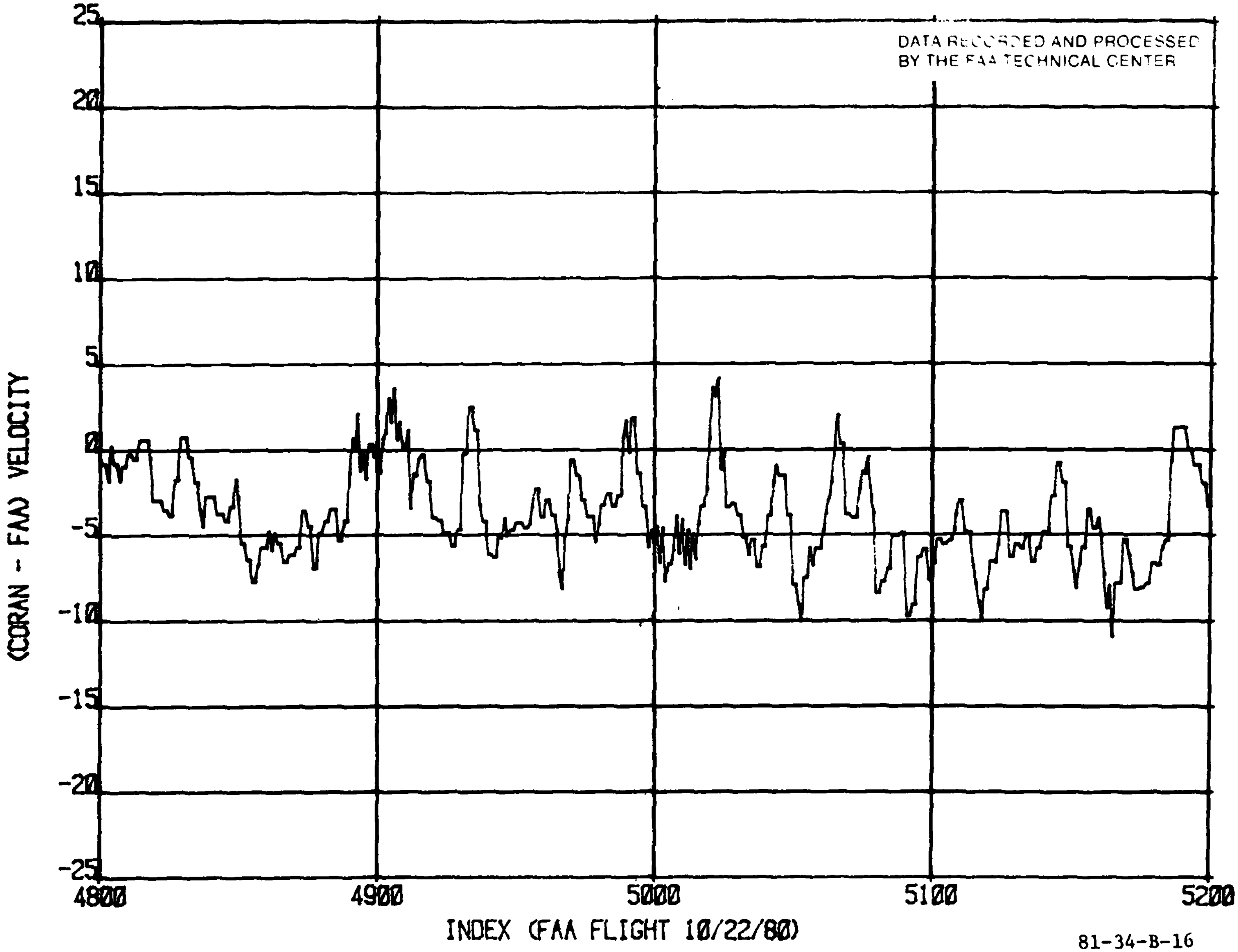
81-34-B-14

FIGURE B-14. VELOCITY DIFFERENCE; (CORAN™-INS) RUN 6, OVER WATER



81-34-B-15

FIGURE B-15. VELOCITY DIFFERENCE; (CORAN™-INS) RUN 7, OVER WATER



81-34-B-16

FIGURE B-16. VELOCITY DIFFERENCE; (CORAN™-INS) RUN 8, OVER WATER

APPENDIX C

ACCURACY OF THE REFERENCE GROUNDSPEED SYSTEM

Information on the accuracy of the reference groundspeed system (a widely-used Inertial Navigation System (INS)) used in the subject test and evaluation is available from the manufacturer's published literature and from flight data obtained at the Federal Aviation Administration (FAA) Technical Center over a long period during which the particular unit used and several other identical units have routinely been employed for groundspeed and position measurements.

During the original certification of this INS for worldwide use by the commercial air fleet, 86 transoceanic flights were made, ranging from 3 to 10 hours in duration. Fifty percent of all such flights produced terminal radial errors of 1 nautical mile or less per hour of navigation time. Eighty-six percent of all the flights produced a terminal radial error of less than 2 nautical miles per hour.

FAA Technical Center results with the INS have, if anything, been better than those obtained during certification. The majority of flights produced a terminal radial error less than 1 nautical mile per hour and, in many cases, as small as 1/2 nautical mile per hour. A routine check is always made of the residual groundspeed after the airplane has been parked at the end of a flight. The groundspeed error has never exceeded 2 knots for any flight, and normally does not exceed 1 knot. Provided that the terminal radial error and the residual groundspeed at the point where the airplane is parked fall within the above stated limits, it is considered reasonable to conclude that the computed position and groundspeed at any time during the flight are at least as accurate. While a detailed test of an INS has not been done at the Center to check on the linearity of the positional and groundspeed drift, spot checks made on many occasions suggest that the errors do grow in a more or less linear fashion with respect to time.

The response of the INS to transients is also discussed in the manufacturer's literature. Under linear acceleration, the transient tilt of the inertial platform can be analyzed as a first order system with a time constant of 100 seconds. For this INS, under a 0.2g acceleration sustained for 100 seconds, the tilt angle rises to about 7°. Over a 10-second period, it is about 1°, which would produce an erroneous acceleration signal of 0.0175g. Assuming that this error grows linearly from 0 at time 0, the resultant velocity error would rise to 1.6 knots in 10 seconds. The error does not grow indefinitely, obviously, since the accelerations are offset by decelerations over a period of time, and the original postulated 0.2g acceleration is a high value in the first place. Under normal operating conditions, the greatest longitudinal accelerations experienced by a transport category airplane are during takeoff and landing. A representative figure for takeoff acceleration is 0.15g (2.86 knots/second), which could exceed the maximum achievable in flight down a 3° degree glide slope.

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